



Supplementary Materials for

Illuminating gravitational waves: A concordant picture of photons from a neutron star merger

M. M. Kasliwal,* E. Nakar, L. P. Singer, D. L. Kaplan, D. O. Cook, A. Van Sistine, R. M. Lau, C. Fremling, O. Gottlieb, J. E. Jencson, S. M. Adams, U. Feindt, K. Hotokezaka, S. Ghosh, D. A. Perley, P.-C. Yu, T. Piran, J. R. Allison, G. C. Anupama, A. Balasubramanian, K. W. Bannister, J. Bally, J. Barnes, S. Barway, E. Bellm, V. Bhalerao, D. Bhattacharya, N. Blagorodnova, J. S. Bloom, P. R. Brady, C. Cannella, D. Chatterjee, S. B. Cenko, B. E. Cobb, C. Copperwheat, A. Corsi, K. De, D. Dobie, S. W. K. Emery, P. A. Evans, O. D. Fox, D. A. Frail, C. Frohmaier, A. Goobar, G. Hallinan, F. Harrison, G. Helou, T. Hinderer, A. Y. Q. Ho, A. Horesh, W.-H. Ip, R. Itoh, D. Kasen, H. Kim, N. P. M. Kuin, T. Kupfer, C. Lynch, K. Madsen, P. A. Mazzali, A. A. Miller, K. Mooley, T. Murphy, C.-C. Ngeow, D. Nichols, S. Nissanke, P. Nugent, E. O. Ofek, H. Qi, R. M. Quimby, S. Rosswog, F. Rusu, E. M. Sadler, P. Schmidt, J. Sollerman, I. Steele, A. R. Williamson, Y. Xu, L. Yan, Y. Yatsu, C. Zhang, W. Zhao

*Corresponding author. Email: mansi@astro.caltech.edu

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Movie S1
Data S1 and S2
Interactive Light Curves for SSS17a

Materials and Methods

Data Reduction

Below we describe the ultraviolet/optical/near-infrared photometric and spectroscopic observations, along with the relevant data reduction. The photometric results from our observations as well as the literature are collected in Table S1. A log of our spectroscopic observations is provided in Table S2.

Gemini-S FLAMINGOS-2 near-infrared imaging

We observed EM170817 fifteen times between 2017 August 18 and 2017 September 15 with the Florida Multi-Object Imaging Near-Infrared Grism Observational Spectrometer (FLAMINGOS-2) imaging spectrograph (54) on the 8.1-m Gemini-S Telescope on Cerro Pachón in Chile (PI Singer, Programs GS-2017B-DD-1, GS-2017B-DD-6). Near-infrared JHK_s imaging data were reduced using standard procedures and calibrated relative to sources from the Two Micron All-Sky Survey (2MASS) (55). Flat fields at each filter position were taken each night of FLAMINGOS-2 observations using the Gemini Facility Calibration Unit (GCAL). Dark frames with identical exposure times to the flat fields and science frames were also taken at least every other observing night. Median sky images were produced from a series of dithered science frames and then subtract to remove atmospheric OH and thermal emission. On nights with poor observing conditions where the sky varied on timescales faster than a full dither series, a subset of the science frames was selected to create the sky frame. The sky-subtracted science frames were then aligned using the centroid of the bright core of the galaxy NGC 4993 and then co-added.

Three 2MASS stars (2MASS J13094767–2321594, 2MASS J13094842–2323499, and 2MASS J13094767–2321594) in the vicinity of EM170817 with the highest photometric quality flag (“A”) in all JHK_s filters were used for flux calibration for all of the FLAMINGOS-2 observations. These three bright standard stars were consistently within the field of view of all the FLAMINGOS-2 observations and thus provide robust calibrators for measuring variability from EM170817.

Due to its proximity to the core of the host galaxy NGC 4993, photometric measurements of EM170817 are contaminated by the extended galaxy emission unless the galaxy is properly subtracted. In order to subtract the extended host galaxy emission, we perform a median filter subtraction of each image before measuring the flux from EM170817. Median filtering

removes small spatial scale features (i.e. point sources) and returns the extended galaxy emission as well as large spatial scale background structures. We then subtract the median-filtered image from the original to remove the extended emission. To avoid self-subtracting emission from EM170817 we set the dimensions of the median filter to ~ 5 times the full-width at half maximum (FWHM) of the point-spread function (PSF) as measured from the 2MASS calibrator stars for each image.

Depending on the signal-to-noise ratio of EM170817, aperture or PSF-fitting photometry was performed. PSF-fitting photometry is preferred due to possible residual emission from the host galaxy NGC 4993 overlapping with the projected position of EM170817 even after the median filter subtraction. However, as EM170817 faded the PSF fitting failed to yield robust photometry ($\text{SNR} > 5$) and thus aperture photometry was used. For aperture photometry, the inner radius of the aperture was set to the FWHM of the PSF as measured from the bright 2MASS calibrator stars. Emission from the sky and residual NGC 4993 background at the position of EM170817 was estimated from a circular annulus centered on EM170817 with an inner and outer radius of 1 and 2 times the FWHM, respectively.

Palomar WIRC near-infrared imaging

We observed EM170817 on 2017 August 27 in the K_s -band using the Wide Field Infrared Camera (WIRC; (56)) on the 200-in. Hale Telescope at Palomar Observatory (P200). Due to the low declination of EM170817 and proximity to the Sun at the time of these observations, we observed the target before 12° twilight at airmass > 7 (elevation $< 10^\circ$). To deal with the bright and rapidly varying sky background we used the minimum exposure time for the WIRC detector of 0.92 s with 8 coadds, allowing us to dither the telescope every ~ 10 s. We obtained 4 well-dithered frames before reaching the elevation limit of the telescope, for a total integration time of 29.44 s. Individual frames were dark-subtracted and flat-fielded. A median sky frame was

constructed from the dithered science images, scaled to the sky level in each individual frame and subtracted to remove the bright background. The individual frames were then aligned and coadded using centroid measurements of 4 well-detected stars, and an astrometric solution was found by comparing to 2MASS. The photometric zero point was also determined by comparing aperture photometry of these stars to their 2MASS magnitudes.

IRSF near-infrared imaging

We observed EM170817 on 2017 August 23, 24, 26, and 28 with the Simultaneous Infrared Imager for Unbiased Survey (SIRIUS) near-infrared (JHK_s) camera (57) installed on the 1.4-m telescope InfraRed Survey Facility (IRSF) telescope at the South African Astronomical Observatory in Sutherland, South Africa (PI Barway, Program Barway-2017-01-IRSF-57). We obtained 10 dithered exposures of 30 s each with dithering radius of 60 arcsec per observing sequence. This was repeated seven to eight times to obtain good SNR. Twilight flat frames were obtained before and after the observations. Dark frames were obtained at the end of the nights. The data reduction steps which include dark frame subtraction, flat-field correction, sky-subtraction, dither combination and astrometric calibration were carried out using the SIRIUS data reduction pipeline software (58). Similar to the FLAMINGOS-2 image processing, we perform a median filter subtraction on the IRSF images to remove the extended galaxy emission before measuring the flux from EM170817.

ANDICAM near-infrared imaging

We observed EM170817 on 2017 August 24–28 with A Novel Dual Imaging CAMera (ANDICAM) instrument (59) mounted on the 1.3-m telescope at Cerro Tololo Inter-American Observatory (CTIO) in Chile (PI Cobb, Program NOAO 2017B-0160). On 2017 August 24, a total of 16 individual 45 s K -band frames were obtained by imaging at 4 different dither positions at each of 4 slightly offset telescope pointings. Each observation from 2017 August 25 to 28 consisted

of a total of 20 individual 90 s K -band frames obtained by imaging at 5 different dither positions at each of 4 slightly offset telescope pointings. After 2×2 binning and flat-fielding of the individual frames, sky frames were produced at each dither position by median-combining all images taken at the same dither position (but with different telescope pointings). Corresponding dither position sky frames were subtracted from each image with rescaling to compensate for variability in background brightness. All sky-subtracted images were aligned and averaged to produce a single master K -band image for each epoch. Finally, we perform a median filter subtraction to remove the extended galaxy emission before measuring the flux from EM170817.

Apache Point Observatory near-infrared imaging

We observed EM170817 in the near-infrared (K_s -band) on 2017 August 27 using the Near-Infrared Camera & Fabry-Perot Spectrometer (NICFPS; (60)) instrument on the Apache Point Observatory 3.5-m telescope (PI Chanover, Program 2017 Q3DD04). Observations were acquired towards the end of evening twilight at high airmass (6–8) through highly variable, partially cloudy conditions. Forty 6 s exposures were acquired, alternating between the source and a position $5'$ away using a dither pattern to move the target to different parts of the detector. Because of rapidly varying clouds, only frames showing stars were used in the image processing. Unregistered frames were combined to form a sky image which was subtracted from each on-source frame. On-source frames were registered using the $K_s = 9.75$ magnitude star 2MASS J13094158–2323149 $1.4'$ away from NGC 4993 and combined into a final image using a median filter after adjusting for the variable background level using the mode of each image. Photometric calibration used the same star as that used for registration.

VLT/VISIR mid-infrared imaging

EM170817 was observed (61) using the Very Large Telescope (VLT) spectrometer and imager for the mid-infrared (VISIR) (62) at the Cassegrain focus of Unit Telescope 3 (UT3) on 2017

August 23, 2017 August 31, 2017 September 01, and 2017 September 06 with the J8.9 filter (central wavelength $8.72\ \mu\text{m}$). Total on-source integration times were 44.8, 17.5, 12.2, and 44.8 minutes, respectively. Chopping and nodding in perpendicular directions with $8''$ amplitudes were used to remove the sky and telescope thermal background.

Observations of EM170817 and standard stars observed on the same night were reduced following the imaging data reduction processes outline in the VISIR Pipeline User Manual: chop and nod frame subtraction, source detection, and shift and add. However, since we did not detect EM170817 or any other point-source in the field of view, the chopping and nodding amplitudes and directions provided in the image headers were used to shift the images before coadding. As a test, we performed the same “blind” shift and add procedure on the images of the standard stars and found that there were negligible differences in the image quality from the properly coadded standard star images. Calibration was performed based on mid-infrared standard stars obtained within same night using the standard-star flux catalog for VISIR imaging filter based on (63).

Gemini-S GMOS optical imaging

We observed EM170817 in the optical (*g*- or *i*-band) several times between 2017 September 1 and 2017 September 5 with the Gemini Multi-Object Spectrographs (GMOS; (64, 65)) at the Gemini-S observatory. The data were reduced and coadded using the GMOS and GEMTOOLS modules in PYRAF. EM170817 was not detected in any of these data. Limiting magnitudes (listed in Table S1) were calculated based on aperture photometry with photometric calibration done relative to the Pan-STARRS PS1 catalogs (66) after utilizing the median subtraction technique described in the FLAMGINOS-2 imaging subsection.

***HST* ultraviolet imaging and astrometric referencing**

We observed EM170817 in the ultraviolet on 2017 August 22 and 2017 August 29 with the *Hubble Space Telescope* (*HST*) Wide Field Camera 3 (WFC3) using the UVIS detectors (PI Kasliwal, Program HST-GO-15436). The first epoch used the F225W and F336W filters (2359 Å and 3355 Å central wavelengths, the latter similar to *U*-band) while the second used the F275W (2704 Å central wavelength) and F336W filters. We calculated PSF magnitudes with the software package DOLPHOT (v.2.0) (67). EM170817 was only detected in the 2017 August 22 F336W image (see figure S1). For the other images we calculated 5-sigma limiting magnitudes based on aperture photometry (see Table S1).

We registered the 2017 August 22 stack of F336W images with the *Gaia* astrometric catalog (68) to derive a more precise position of EM170817. With 22 matched *Gaia* sources the refined astrometric solution has root-mean-square residuals of 0.05'' and we measure the position of EM170817 to be (J2000) Right Ascension 13^h09^m48.071^s, Declination $-23^{\circ}22'53.37''$.

Gemini-S FLAMINGOS-2 near-infrared spectroscopy

We observed EM170817 on 2017 August 22 and 2017 August 29 with the FLAMINGOS-2 spectrograph (54) on the 8.1-m Gemini-S Telescope on Cerro Pachón in Chile. For the first epoch we used the 3-pixel ($0.54''$ wide) slit and obtained spectra with both the JH and HK grism/filter sets to achieve a spectral resolving power of 600 across the $1.0\text{--}2.4\,\mu\text{m}$ spectral range. Using an exposure time of 150 s, we obtained a sequence of 6 frames in the JH setup and 8 frames in the HK setup. The target was nodded along the slit between frames in an ABBA pattern to allow for accurate subtraction of the sky background. Baseline calibrations were also obtained, including dark frames, spectral flat fields, Ar arc lamp spectra for wavelength calibration, and observations of the A0V star HIP 69718 immediately after the science observations at similar airmass. For the second epoch we increased the total integration time to 16 frames of 150 s each using the HK setup.

Dark current subtraction, flat-fielding, sky background subtraction, coadding of the 2D spectra, wavelength calibrations, and 1D extractions were performed using standard tasks in the Gemini IRAF package. Telluric corrections and flux calibrations were performed using the IDL tool XTELLCOR (69). A model spectrum of Vega was used to match and remove the hydrogen lines of the Paschen and Brackett series from the A0V telluric standard and construct a telluric correction spectrum free of stellar absorption features. The resulting telluric correction spectrum was also used for the initial flux calibration. The absolute flux calibration was then found by comparing synthetic photometry derived from the spectra to the H -band photometric measurement of the transient at the same phase. In the second epoch, despite the increased exposure time we did not detect EM170817.

Gemini-S GMOS optical spectroscopy

We observed EM170817 on 2017 August 20 and 2017 August 21 using the Gemini Multi-Object Spectrographs (GMOS; (64, 65)) on the 8.1-m Gemini-S Telescope on Cerro Pachón in Chile with the R400 and B600 gratings. The spectra were reduced using the Gemini IRAF package (70). The standard star EG274 was observed on 2017 August 20 and used to flux-calibrate spectra from both of the observed epochs. Both spectra show largely featureless continua. The observations taken on 2017 August 21 show a clear trace on both the blue and red sides of the detectors. The trace on the blue side of the observation on 2017 August 20 was too weak to extract.

Keck LRIS optical spectroscopy

We observed EM170817 on 2017 August 25 using the Low-Resolution Imaging Spectrometer (LRIS; (71)) on the 10-m Keck I telescope. The visibility of the target was poor and the observations were conducted under non-optimal conditions at the end of evening twilight, with the airmass in the direction of the target increasing from 3.8 at the start of the sequence to ~ 6 at the end of the final exposure. We used the D560 dichroic to split the light between the red and blue sides, and used the 400/8500 grating on the red side and the 400/3400 grism on the blue side. The observations were processed using the analysis pipeline LPIPE (72) and summed. A weak trace is visible at the transient location on the red-side camera. Our low-signal-to-noise ratio extraction of the spectrum (figures S2 and S3) shows a featureless red continuum with no significant features (in particular, no broad or narrow emission lines), although we note that a clean extraction is complicated by the significant contamination from the spatially-varying host galaxy continuum.

Bolometric Light Curve Construction

We combined available ultraviolet, optical, and near-infrared photometric data (including our data along with data published in the LIGO/Virgo collaboration (LVC) Gamma Ray Coordinates Network (GCN) circulars; Table S1) on EM170817 to build a bolometric light curve using two independent approaches illustrated in figure 2. All analysis used a distance of 40 Mpc (73, 74) and a reddening of $E(B - V) = 0.1$ mag (75).

Our first method uses low-order polynomials to enable interpolation of the photometry in the individual filters. A blackbody is then fitted to the interpolated photometry for a set of discrete epochs starting from 0.49 d after GW170817 (0.04 d after the first i -band detection) up until 12.9 d after GW170817. Second, we fit the data with an evolving blackbody model by assuming a functional form for the time-dependence of the blackbody temperature $T(t)$ and the radius $R(t)$. After experimenting with different models we found the best functional forms to be $R(t) = R_0(1 - e^{-\lambda_R t}) + vt$ (a model that initially decelerates and then coasts) and $T(t) = T_0 t^{\alpha_T}$, where R_0 is a reference radius, v is an expansion speed, λ_R is a deceleration rate, T_0 is a reference temperature at time $t = 0$, and α_T is a temperature power-law exponent. The data were fit by computing the monochromatic flux density as a function of time and wavelength appropriate for each observation (corrected for extinction assuming $A_V = 0.31$ mag, and using the reddening law of (76) when no instrument-specific reddening data was available) and comparing with the data; no interpolation or binning was used on the data themselves. The parameter fitting was done using a Markov Chain Monte Carlo method (77): we used 80 walkers, ran for 50 iterations to achieve “burn-in”, and then ran for a further 1000 iterations, only using every 41st value to account for finite autocorrelation in the resulting chains. We then determined the best-fit parameter values and uncertainties from the posterior distributions. We restricted the fit to times ≤ 12.5 d after GW170817, since after that time the multi-wavelength coverage was significantly diminished and we typically only had detections in a single band

(K_s). Our best-fit values and uncertainties (68% confidence limits) are $R_0 = 24000 \pm 3000 R_\odot$, $v = 2500 \pm 300 R_\odot \text{ d}^{-1} = 20000 \pm 3000 \text{ km s}^{-1}$, $\lambda_R = 0.42 \pm 0.05 \text{ d}$, $T_0 = 6050 \pm 50 \text{ K}$, and $\alpha_T = -0.62 \pm 0.01$, with t in days. A model with λ_R finite (i.e., initially decelerating) is preferred over a model with constant velocity: χ^2 is reduced by 600 with roughly 140 degrees-of-freedom.

Overall both approaches give us consistent results for effective temperature, photospheric radius and kinematics (see main text and figure 2). With neither approach do we compute a formal goodness-of-fit, as our data-set is too inhomogeneous. We are drawing data from 24 different telescopes, with many photometric systems, filter transformations, extinction coefficients, and zero-points, not all of which are fully documented. There are also significant variations in calibration methodology and host-galaxy subtraction, all of which can affect the resulting photometry. We have manually removed the data where host subtraction was known to be problematic but do not perform quantitative model evaluation (e.g., for deviations from blackbodies).

Supplementary Text

Census of the Local Universe Galaxy Catalog

We used a galaxy catalog to narrow down our candidate transients within the gravitational wave trigger volume and provide basic and physical properties for each of the galaxies within that volume. We find that the galaxies in the 90% volume span a large range of properties containing low-mass dwarfs as well as larger galaxies (spirals and ellipticals).

The Census of the Local Universe (CLU) galaxy catalog consists of two parts: a compilation of known galaxies from many sources; and new galaxies (i.e., those with no previous distance information) from a four-filter, narrowband survey designed to find redshifted $H\alpha$ emission out to 200 Mpc (based on conservative predictions for the horizon of NS-NS detections with LIGO/Virgo (78, 79)) across $\approx 3\pi$ of the northern sky. In this case, the gravitational wave localization was confined to a declination (near -25°) below the southern limit of the narrowband survey ($\delta \geq -20^\circ$), so only the compiled galaxy catalog overlapped with the GW event and will be described here.

The compiled portion of the CLU galaxy catalog (80) was taken from existing galaxy databases: NASA/IPAC Extragalactic Database (NED), Hyperleda (81), the Extragalactic Distance Database (EDD; (82)), the Sloan Digital Sky Survey data release 12 (SDSS DR12; (83)), and the Arecibo Legacy Fast Arecibo L-band Feed Array survey (ALFALFA; (84)). The catalog contains $\sim 260,000$ galaxies with spectroscopic distances less than 200 Mpc. The current version of the catalog contains updates from both NED and SDSS in early 2016. Distances based on Tully-Fisher methods were favored over kinematic (i.e., redshift) distances because of the large contribution of peculiar velocities in this local sample; however, the majority of the distances are based upon redshift information.

In addition to distances, the catalog also contains compiled multi-wavelength photomet-

ric information. We have cross-matched the CLU catalog with *Galaxy Evolution Explorer* (*GALEX*) all sky catalog (85), the *Wide-field Infrared Survey Explorer* (*WISE*) all sky catalog (86), and SDSS DR12 (83) to obtain fluxes from the ultraviolet (UV) to the infrared (IR), with $\sim 104,000$ matches for the *GALEX* far-ultraviolet (FUV, 1500 \AA) band, $\sim 226,000$ for the *WISE* 3.4 and $22 \mu\text{m}$ bands, and $\sim 114,000$ for the SDSS r -band.

We spatially cross-matched the CLU galaxy catalog to the 90% containment volume of the LIGO/Virgo trigger (5) reported by the BAYESian TriAngulation and Rapid localization (BAYESTAR) probability sky map (87) with no assumption on orientation and found 49 galaxies. In addition, we have used the *GALEX* FUV and *WISE* 3.4 and $22 \mu\text{m}$ bands to measure the physical properties of these galaxies. The star formation rates (SFRs) are derived from *GALEX* FUV Kron-magnitudes (88) after correcting for Milky Way extinction (75) as tabulated by NED and internal dust extinction using a combination of observed *GALEX* FUV and *WISE* $22 \mu\text{m}$ fluxes (89). The stellar masses (M_\star) are derived from $3.4 \mu\text{m}$ ALLWISE fluxes and a mass-to-light ratio of $0.5 M_\odot/L_\odot$ (90).

Table S3 lists the basic properties of the 49 galaxies (sorted by stellar mass) along with the UV and IR fluxes, SFRs, stellar masses, and the probabilities in the containment volume (91). The galaxies span ranges of stellar mass ($10^7 M_\odot$ to $10^{10.5} M_\odot$) and SFR ($10^{-2.6} M_\odot \text{ yr}^{-1}$ to $10^{0.5} M_\odot \text{ yr}^{-1}$) suggesting that the list contains dwarfs as well as larger more massive galaxies.

Host Galaxy NGC 4993

Basic Properties

The EM counterpart for GW170817, EM170817, was reported near NGC 4993, the third most massive of the galaxies cross-matched to the LIGO/Virgo trigger by the Census of the Local Universe project (91) (NGC 4993 was not present in the top 15 galaxies in the Galaxy List for the Advanced Detector Era catalog (92) and reported in (93), although it is present in their on-line catalog). NGC 4993 has been classified as an E-S0 galaxy with a morphological T-type of -3 (94) at a distance of roughly 40 Mpc, based on Tully-Fisher measurements of other galaxies in its group (73, 74). Archival *HST*/Advanced Camera for Surveys (ACS) F606W data (Program ID: 14840; PI Bellini) show complicated dust lanes extending a few kpc from the nucleus (95, 96) superimposed on an elliptical galaxy, similar to many other early-type galaxies. The dust lanes may be the result of a minor merger that occurred as long as several Gyr ago. Note that the dust lanes do not extend across the position of EM170817 (figure S1), suggesting EM170817 is not located in a heavily-obscured region. This is echoed by examination of spatially-resolved spectra, which show no emission-lines within $\pm 5''$ (± 1 kpc) of the transient, and our *HST* UV images which show very little emission at the position of the EM170817 (Figure S1).

Archival optical spectra (97, 98) show a continuum dominated by old stars with a pronounced 4000 Å break indicative of little if any active star formation; [NII], [SII], and weak [OIII] emission lines are present in the nucleus with likely some $H\alpha$ emission filling in the Balmer absorption from the stellar continuum, but the relatively high [NII]/ $H\alpha$ ratio is suggestive of a low-luminosity active galactic nucleus (LLAGN) rather than star formation.

We estimated the Eddington ratio for the central black hole by computing the bolometric luminosity L_{bol} from the X-ray luminosity ($5.6 \times 10^{39} \text{ erg s}^{-1}$; (99)) assuming a ratio of bolometric to X-ray flux of 16 for LLAGNs (100), while the Eddington luminosity L_{Edd} is determined from black hole mass obtained from the central velocity dispersion (163 km s^{-1} ; (97)); these imply

$L_{\text{bol}}/L_{\text{Edd}} = 1.4 \times 10^{-5}$, which is similar to ratios of other LLAGNs (100).

Constraints on the NS-NS Merger Timescale

To further constrain the timescale of NS-NS mergers, we investigated star formation histories of NGC 4993 by fitting the spectral energy distribution (SED) with the package MAGPHYS. MAGPHYS uses stellar population syntheses code (101, 102) to provide spectral evolution at wavelengths from 912 Å to 1 mm and at ages between 1×10^5 and 2×10^{10} yr. We collected photometric data from the *GALEX* (NUV and FUV; (85)), Pan-STARRS1 (*grizy*; (66)), 2MASS (*JHK_s*; (55)), *WISE* (W1, W2, W3, W4; (86)) and *IRAS* (60 μm; (103)) surveys, where we used upper limits for the *GALEX*/FUV and *IRAS*/60 μm bands (Figure S7). The best-fit model gives the stellar mass of the galaxy $M_{\star} \sim 3 \times 10^{10} M_{\odot}$ and the star formation rate (SFR) $\sim 3 \times 10^{-3} M_{\odot} \text{ yr}^{-1}$. There appears to be an offset between the data and the model in the region near the near-infrared (2MASS *JHK_s*) and mid-infrared (*WISE*) observations. This may reflect different methods of measuring the entire extent of NGC 4993 used for the different catalogs.

For comparison, the SFR derived from *GALEX*/FUV is $\sim 4 \times 10^{-2} M_{\odot} \text{ yr}^{-1}$, the SFR from *GALEX*/NUV for stars more massive than $5 M_{\odot}$ is $\sim 3 \times 10^{-3} M_{\odot} \text{ yr}^{-1}$ (104, 105), and the SFR from the *IRAS*/60 μm upper limit is $< 0.08 M_{\odot} \text{ yr}^{-1}$ (106, 107). Given the varying systematics and uncertainties in both the data and the methods, we consider these to be largely consistent and indicative of small levels of ongoing star-formation, with SFR of 10^{-3} to $10^{-2} M_{\odot} \text{ yr}^{-1}$. This is consistent with estimates based on the non-detection of neutral hydrogen (108). The estimate of the SFR is an upper limit because of the possible contamination of the central LLAGN.

The time since the last burst of star formation ended is ~ 2 Gyr, implying a relatively long timescale for the merger of the NS-NS binary system since progenitors of neutron stars are short-lived. Even a more conservative limit based on the absence of early-type stars in the

spectrum puts the last episodes of star-formation more than a Gyr ago. This is not consistent with previous predictions that the delay time of NS-NS mergers is short (1–100 Myr; (109,110)), although there are Galactic NS-NS binaries with merger times 100 Myr–10 Gyr (e.g., (111)). In addition, population synthesis of compact object mergers finds significant numbers of sources produced after Gyr delays, with the progenitor systems formed at high redshift during the peak epochs of star formation (e.g., (112)).

Models

In the sections below, we discuss several details of models to explain the overall electromagnetic emission from EM170817. We estimate the maximum ejecta mass possible to have a weak, on-axis, ultra-relativistic jet break out. We then consider a model where the observed γ -rays are produced by an off-axis short γ -ray burst (sGRB). We consider a structured jet and a strictly Newtonian source. This motivates us to describe the analytical and numerical details of our preferred model: a shock breaking through a cocoon of material. Finally, we consider alternative sources of an engine-driven wind and free-neutron decay to power the early-time emission.

A Weak On-Axis Jet

The observed γ -rays carried an isotropic equivalent energy of $\sim 3 \times 10^{46}$ erg over a duration of ~ 2 s, corresponding to an average luminosity of $\sim 1.5 \times 10^{46}$ erg s $^{-1}$ (3, 4). sGRB jets produce γ -rays very efficiently (e.g., (37)), so if we observe a regular on-axis GRB the total jet isotropic equivalent energy is at most a few times larger than that of the observed γ -rays. Therefore, to evaluate if the observed γ -rays could have been produced by a weak on-axis jet we estimate the maximum ejecta mass that a jet with an opening angle θ_j and isotropic equivalent luminosity 10^{47} erg s $^{-1}$ can cross within 2 s. We approximate the ejecta as being static and spherical, with a density profile $\rho \propto r^{-2}$, where ρ is the density and r is the radius. We assume a typical ejecta velocity of $0.2c$, a breakout time of 2 s and $r = 10^{10}$ cm. We use a jet propagation model (113) which was calibrated numerically (114) to estimate the breakout time (115). We find that for $\theta_j = 10^\circ$ a breakout of 2 s is achieved for mass $< 3 \times 10^{-6} M_\odot$. For $\theta_j = 30^\circ$ the upper limit on the mass is lower by about an order of magnitude.

To verify this calculation we carried out a numerical simulation where a jet is launched into expanding ejecta. We use an identical setup to the one described in the main text with a

few minor changes as follows: we choose a simple radial density profile without an angular component with a power-law index of 3.5 rather than 2, and omit the extended ejecta. The jet has the same properties as in the main text but with a lower isotropic luminosity of $10^{-47} \text{ erg s}^{-1}$ and shorter delay time of 0.1 s between the merger and its launch (a short delay decreases the breakout time). The grid setup is similar, but extends only up to the breakout radius. We varied the ejecta's total mass until the breakout took place at 2 s, which happened near a mass of $2.5 \times 10^{-6} M_{\odot}$, very close to the analytic prediction.

Observational and theoretical considerations indicate that the amount of mass that was ejected at high latitudes along the jet path is higher than $10^{-5} M_{\odot}$ by orders of magnitude. First, the bright optical emission during the first day implies that about $0.02 M_{\odot}$ with a relatively low optical depth (assuming $\kappa \approx 1 \text{ cm}^2 \text{ g}^{-1}$) were ejected. This type of material is expected to be synthesized after the merger in the high latitude wind that is exposed to a high neutrino flux (e.g., (116)). Second, optical/IR emission indicates that the total ejected mass is at least $0.05 M_{\odot}$, and while this mass is most likely not distributed isotropically, numerical simulations show that all mass ejection processes throw a non-negligible fraction of mass at high latitudes (e.g., (30, 116, 117)). Moreover, all these simulations find that the high latitude ejecta mass is larger than about $10^{-3} M_{\odot}$. We therefore conclude that the observed γ -rays are highly unlikely to be produced by an on-axis low-luminosity jet.

An Off-Axis Jet

A potential explanation for the extremely low luminosity of the observed γ -ray emission of EM170817 is that we observe a regular luminous sGRB, but our line-of-sight is outside of the GRB jet and the low luminosity is due to the lower Doppler boost compared to an on-axis observer. Below we examine the implications of such a configuration.

Consider a jet with an opening angle θ_j and a Lorentz factor $\Gamma \gg 1$ that radiates γ -rays. An

on-axis observer sees γ -ray emission with a total energy E , a typical photon energy E_p and a total duration Δt . We are interested in what an off-axis observer at a viewing angle $\theta_{\text{obs}} > \theta_j$ will see. We define the quantity $q = (\theta_{\text{obs}} - \theta_j)\Gamma$ since for an off axis observer $q \gg 1$ and the Doppler boost ratio to an on-axis observer is $\propto q^{-2}$. We denote all the off-axis observables with prime.

The effect of the Lorentz boost on the photons' energies implies:

$$\frac{E_p}{E'_p} = q^2 \quad (\text{S1})$$

The observed total isotropic equivalent energy (fluence) ratio has three regimes, depending on how far the observer is from the edge of the jet and how wide the jet is compared with $1/\Gamma$:

$$\mathcal{A} \equiv \frac{E}{E'} = \begin{cases} q^4 & ; \quad \theta_{\text{obs}} - \theta_j \ll \theta_j \quad (i) \\ q^6(\theta_j\Gamma)^{-2} & ; \quad \theta_{\text{obs}} - \theta_j \gg \theta_j > 1/\Gamma \quad (ii) \\ q^6 & ; \quad \theta_j < 1/\Gamma \quad (iii) \end{cases} \quad (\text{S2})$$

where we define an amplification parameter $\mathcal{A} \equiv E/E'$. To understand this equation it is most convenient to consider first the last case, $\theta_j < 1/\Gamma$, since then the jet can be regarded as a point source. If $\theta_{\text{obs}} - \theta_j \gg \theta_j > 1/\Gamma$ then the whole solid angle of the jet (θ_j^2) contributes roughly equally to the observed fluence for an off-axis observer, compared to a solid angle $1/\Gamma^2$ that dominates the emission for an on-axis observer, thereby reducing the fluence ratio by a factor of $(\theta_j\Gamma)^2$. Finally, when $\theta_{\text{obs}} - \theta_j \ll \theta_j$ the whole jet does not contribute equally to an off-axis observer and the emission is dominated roughly by a solid angle of $(\theta_{\text{obs}} - \theta_j)^2$.

The observed duration depends on the details. If we assume that each observed pulse has a duration δt and that it is generated by an episode of emission that takes place at a radius r over some radii range $\Delta r \sim r$ then $\delta t \approx r/(2c\Gamma^2)$ and

$$\frac{\delta t}{\delta t'} = q^{-2} \quad (\text{S3})$$

If the total on-axis duration is determined not by a single episode, but by the radial length of the jet (as in the case of internal shocks for example) then

$$\Delta t' = \max\{q^2 \delta t, \Delta t\} \quad (\text{S4})$$

For EM170817 $E' \approx 3 \times 10^{46} \text{ erg}$ (3, 4). If the on-axis observer sees a regular sGRB then $\mathcal{A} = 10^3 - 10^6$ with a typical value of $\mathcal{A} = 10^4$. A value $\mathcal{A} = 10^3$ may be too low due to the requirement that the jet breaks out of the ejecta within 2 s, as a jet with a luminosity of $10^{50} \text{ erg s}^{-1}$ can break out on time only if the ejecta mass along its path is $< 10^{-3} M_\odot$ (isotropic equivalent). This is much lower than the total mass we observed assuming an opacity $\kappa \approx 1 \text{ cm}^2 \text{ g}^{-1}$ of $\sim 0.02 M_\odot$ (see main text), which is ejected presumably at high latitudes.

Classical sGRBs show non-thermal spectra and therefore the observed photons are expected to be generated above or near the photosphere. This expectation was one of the main indications that GRB jets are relativistic (118, 119) and it still provides the most robust lower limit on the Lorentz factor of GRB jets. The optical depth of a relativistic jet τ_Γ that radiates a spectrum with a power-law and exponential cutoff, $N_\nu \propto \nu^\alpha \exp[-h\nu/E_0]$, such as the one seen in EM170817, is given by (36):

$$\tau_\Gamma \approx 10^{13} L_{51} \delta t_{-2}^{-1} \frac{m_e c^2}{E_0} \Gamma^{-(4-\alpha)} \exp \left[-\frac{\Gamma m_e c^2}{E_0} \right] \quad (\text{S5})$$

where L_x is the burst luminosity in units of 10^x erg s^{-1} , δt_x is the single-pulse duration in units of 10^x s , and $m_e c^2$ is the electron rest-mass energy. This expression can be written using the off-axis observables and \mathcal{A} :

$$\tau_\Gamma \approx 10^7 \mathcal{A} L'_{47} \delta t_0'^{-1} \frac{m_e c^2}{E_0'} \Gamma^{-(4-\alpha)} \exp \left[-\frac{\Gamma m_e c^2}{E_0'} \right] \quad (\text{S6})$$

There is still a dependence on the on-axis observed E_0 in the exponent of this equation, for which the transformation to the off-axis frame depends on \mathcal{A} differently for each of the three regimes in equation S2. Therefore the limit on Γ that we derive below is different for each regime.

The requirement that the γ -ray source is optically thin, i.e., $\tau_{\Gamma} < 1$, provides a lower limit on the jet Lorentz factor $\Gamma(\mathcal{A})$, which in turn determines the maximal distance the observer can be from the edge of jet (i.e., $\theta_{\text{obs}} - \theta_j$) for each value of \mathcal{A} . Figure S8 shows that distance for cases (i) and (iii) which are independent of θ_j . The results for case (ii) are similar for all realistic values of θ_j . This suggests that for $\theta_{\text{obs}} \approx 0.5$ rad we can never be in the far regimes, i.e., (ii) or (iii) since $\theta_{\text{obs}} - \theta_j \ll \theta_j$ is always true. Figure S9 shows the minimal Lorentz factor of the jet only for case (i) (near miss). This implies that if the observed γ -rays are generated by an off-axis jet then it must have $\Gamma > 100$ and the angle between us and the jet's edge cannot exceed 0.1 rad.

A luminous jet that the observer missed by only 0.1 rad is expected to produce a very bright afterglow roughly a day after the burst. The blast wave driven into the circum-merger medium, which produces the afterglow, decelerates to a Lorentz factor < 10 by that time and thus its cone of emission enters the observer's line of sight. Hence, after about 1 d the observer sees a regular sGRB afterglow. Limits on the X-ray and radio rule out this option (15, 18). The only way to avoid a bright afterglow is if the merger took place in an environment with a very low circum-burst density. In fact, taking the minimal Lorentz factor allowed by compactness (i.e., the maximal distance to the jet edge), and a typical sGRB energy with $\mathcal{A} = 10^4$, the circum-burst number density should be as low as $\sim 10^{-6} \text{ cm}^{-3}$ for the afterglow to be consistent with the observed limits and detections in the X-ray and the radio. This value is lower by orders of magnitudes than the density inferred by sGRB afterglows (120) and for this specific event it is unexpected given the modest offset of the merger location from the center of NGC 4993 (although we do not know the offset along the line-of-sight). It would be more typical of the intergalactic medium (121). Moreover, based on neutral hydrogen mass functions, a density of 10^{-6} cm^{-3} is ten times less likely than 10^{-3} cm^{-3} in early type galaxies (122). In addition, if EM170817 were an off-axis sGRB, then an on-axis observer would have seen a burst with

a typical photon energy of $E_p \approx 10 \text{ MeV}$, much higher than the values observed in sGRBs (123, 124). Finally, the probability to have such a near miss of the jet is only a few percent. In fact the chance to see a regular on-axis GRB is significantly higher in that case, since the jet is relatively wide ($\approx 0.4 \text{ rad}$).

To conclude, in order for the EM170817 to be an off-axis sGRB, in addition to fortuitous alignment all of the parameters need to be at their limits. The Lorentz factor would be the lowest one allowed by the compactness limit and the surrounding density would be extremely low. In addition, the on-axis sGRB should have an E_p that is much higher than that observed in sGRBs. This implies that it is unlikely that EM170817 is generated by an off-axis observation of a typical sGRB.

A Structured Jet

We consider the possibility that sGRB jets have structure – a core with high-luminosity and high Lorentz factor; wings with lower luminosity and/or lower Lorentz factor. This structure may be induced by the jet launching mechanism or by the interaction of the jet with the ejecta. The question then is whether the observed γ -rays could have been generated at the jet's wings, either on-axis or off-axis. Below we consider both options.

If we observe the wings on-axis, then these are wide-angle low-luminosity wings. It is unclear how such wings would be generated. If a jet is launched with a high luminosity narrow core and low-luminosity wide angle wings, then the situation is similar to the on-axis wide and weak jet discussed above. The propagation of the narrow core does not facilitate the propagation of the wide low-luminosity wings, which will be choked by the ejecta. The interaction with the ejecta is also unlikely to produce low-luminosity wide wings because a cocoon, which has a comparable energy to the jet itself, is expected to dominate the wide angle outflow.

Off-axis emission from moderate Lorentz factor (say $\Gamma \sim 10$) material at the jet wings is

more plausible. In this scenario the lower Lorentz factor of the jet wings allows the γ -rays to be observed although the angle to the jet edge is large enough that the afterglow emission will not violate the X-ray and radio observations. However, this configuration is also in tension with the observations. First, the compactness criterion that we used in order to constrain the off-axis emission (see above) shows that material with low Lorentz factor that is observed off-axis cannot have a high amplification factor \mathcal{A} . Namely it must have low luminosity. For example a source with $\Gamma \approx 10$ is limited to $\mathcal{A} \approx 20$, or a total isotropic equivalent energy of $\sim 6 \times 10^{47}$ erg as seen by an on-axis observer. Such low energy material is again expected to be suppressed by the cocoon. Moreover, observations of sGRBs do not support a structured jet with a luminosity that gradually drops at the wings. The reason is that with such a structure we would expect to detect at least some sGRBs where the γ -rays are generated by the low-luminosity wings that point towards us. The afterglows from these GRBs would have shown after a day or so the signature of an off-axis jet that carries significantly more energy than the one observed in γ -rays, once the emission becomes dominated by the high energy core. Such sGRBs are not observed (see for example a compilation of sGRB prompt and afterglow properties by (37)).

We conclude that while in principle the observed γ -rays may have been generated by low-luminosity low-Lorentz factor wings of a jet seen off-axis, current observations and theory disfavor this possibility.

A Newtonian γ -ray source

Assume that the γ -ray source is Newtonian. The optical depth of the source, due to produced pairs, can be estimated using equation S5 with $L_{51} = 10^{-5} - 10^{-4}$ (3, 4) and $\delta t_{-2} \approx 100$. Thus, if $\Gamma = 1$ the source is extremely opaque. If we assume the maximal possible radius given the burst duration $\sim 3 \times 10^{10}$ cm, the lower limit on the optical depth at the source is $\approx 10^5 - 10^6$. Such a large optical depth is unrealistic for many reasons. For example, the observed spectrum

below E_p is much shallower (softer) than a blackbody, while the spectrum of such a source is expected to be a blackbody or a Wein (3, 4). Another problem is the implied diffusion time. The burst duration must be shorter than the diffusion time, which with this optical depth implies that the width of the emitting region cannot exceed $\sim 10^5$ cm during the entire emission. Such a narrow non-expanding emitting region is not expected in ejecta that expands at sub relativistic velocities at a radius of $\sim 3 \times 10^{10}$ cm.

Thus, we conclude that the γ -ray source must have a low optical depth. Equation S5 shows that $\Gamma = 2 - 3$ (mildly relativistic) is sufficient for an optically thin source.

A Mildly Relativistic Shock Breakout of a Cocoon

When a fast shock propagates in a high optical depth medium, it is dominated by radiation. The shock breaks out once the optical depth drops such that the radiation is not confined within the shock layer and escapes to infinity. The theory of relativistic shock breakout was developed in the context of a shock that propagates in a star (125, 126) where the unshocked material is static and the stellar structure dictates its propagation. In the scenario of a breakout from the ejecta of a binary neutron star merger the shock breaks out of expanding material, which has a different density profile than a star. Nevertheless, since the pulse of radiation that is emitted upon the shock breakout is dominated by the radiation generated within a very thin layer with an optical depth of unity, its properties depend almost entirely on two physical parameters: the shock Lorentz factor, Γ_{bo} , and the breakout radius, R_{bo} . Thus, we can use the derivation of (126) to test whether a shock breakout can produce the observed signal, and if it does then to estimate its properties.

Not every flare of γ -rays can be generated by a relativistic shock breakout. First, shock breakouts do not produce flares with a highly variable temporal structure. This by itself implies that almost no GRBs (short or long) could be generated by shock breakouts. Second, the three

main observables of the flare: energy, E_{bo} , duration t_{bo} and temperature, T_{bo} (note that the spectrum is not expected to be a blackbody, and T_{bo} is just the typical photon energy), depend only on two physical parameters, Γ_{bo} and R_{bo} . Therefore they must roughly satisfy a closure relation (I26):

$$t_{\text{bo}} \sim 1 \text{ s} \left(\frac{E_{\text{bo}}}{10^{46} \text{ erg}} \right)^{1/2} \left(\frac{T_{\text{bo}}}{150 \text{ keV}} \right)^{-\frac{9+\sqrt{3}}{4}} \quad (\text{S7})$$

The flare of γ -rays that followed EM170817 (3, 4), which released $E_{\text{bo}} \approx 4 \times 10^{46} \text{ erg}$ over a duration of $t_{\text{bo}} \sim 1 - 2 \text{ s}$ at a typical photon energy of $T_{\text{bo}} \sim 100 - 150 \text{ keV}$, satisfies the relation. Again, almost all the regular GRBs (short and long) do not satisfy this relation. They are too energetic and soft for their duration. The only type of GRB that satisfies equation S7 and shows a non-variable light curves are low-luminosity GRBs, for which we have strong evidence that the γ -rays are generated by a mildly relativistic shock breakout (I27).

Using any two of the three equations 14, 16 17 from (I26) we can find that if a shock breakout is the source of the γ -rays that followed GW170817 then $R_{\text{bo}} \sim 3 \times 10^{11} \text{ cm}$ and $\Gamma_{\text{bo}} \approx 2 - 3$. Equation S7 and the estimates of the breakout parameters both assume that the shock breakout takes place over a relatively wide angle ($> 20^\circ$) that includes the observer's line-of-sight. This implies that in the case of EM170817 the cocoon breakout must have taken place over a wide angle of at least $0.5-1 \text{ rad}$ if it was the source of γ -ray emission.

Hydrodynamical Simulation of A Cocoon Breakout

To verify that a model of a cocoon driven by a choked jet can explain the full range of electromagnetic observations, we carry out 2D relativistic hydrodynamic simulations, followed by a post-processing calculation of the UV/Optical/IR emission during the expansion of the cocoon and the ejecta. We search for a model in which the delay between the merger and the observed photons from the breakout is 2 s (3, 4) and that its breakout radius and velocity match those that we calculate above. We do not directly calculate the γ -ray signal since the breakout takes place

over a scale that is much smaller than the scales that our simulation can resolve. However, the model is required to match the UV/Optical/IR observations.

For the 2D relativistic hydrodynamic simulations we use the public code PLUTO (128). The initial configuration at $t = 0$ (defined as the merger time) is cold ejecta that expands radially, which is present from the base of the grid at $r_{\text{esc}} = 4 \times 10^8$ cm up to $r_{\text{max}} = 2 \times 10^9$ cm. The ejecta have an angular profile, where most of the mass (75%) is near the equator at $\theta > 1.0$ rad, where θ is the polar angle. The ejecta are also divided in the radial direction into two regions (with similar angular profiles) – a massive slow core that extends at $t = 0$ up to $r_c = 1.3 \times 10^9$ cm and low-mass fast material that extends at $t = 0$ between r_c and 2×10^9 cm. The density profile of the dense core is:

$$\rho_{\text{core}}(r, \theta) = \rho_0 r^{-2} \left(\frac{1}{4} + \sin^3 \theta \right), \quad (\text{S8})$$

where ρ_0 is the normalization which is chosen to fix the total ejecta mass. The velocity profile of the core is

$$v_{\text{core}}(r) = v_{\text{c,max}} \frac{r}{r_c}, \quad (\text{S9})$$

where $v_{\text{c,max}} = 0.2c$ is the maximal velocity of the ejecta's inner part. The extended ejecta density profile is chosen as a very steep power-law in v between $v_{\text{c,max}}$ and $0.8c$ so its total mass is 1% of the core mass and the mass carried by material at $v > 0.7c$ is about 10^{-5} of the total ejecta mass. The jet is injected into the ejecta with a delay of 1 s for a total working time of 2 s and a total luminosity of L_j . The jet is injected with a specific enthalpy of 20 (in units of its rest-mass energy) at an opening angle of 0.7 rad from a nozzle at the base of the grid with a size of 10^8 cm. We search for a model that fits the evolution of the bolometric luminosity and temperature fitted to the UV/optical/IR data by varying the total ejecta mass, namely ρ_0 , and the jet's luminosity, L_j . We find reasonable fits with ejecta masses larger than $0.05 M_\odot$ and jet luminosities that release an energy that is comparable or slightly larger than the total ejecta kinetic energy. The specific model presented in the paper (figs 2 and 6) and which is discussed

below has a total ejecta mass of $0.1 M_{\odot}$ and jet luminosity $L_j = 2.6 \times 10^{51} \text{ erg s}^{-1}$.

Given its large opening angle the jet is not collimated. Instead it works its way through a large amount of ejecta dissipating its energy in the process, forming a cocoon. The jet injection stops at 3 s and by $t \approx 4$ s the jet is fully choked, leaving a hot cocoon that continues to propagate driving a mildly relativistic ($\Gamma \approx 2 - 3$) shock into the ejecta. About 10 s after the merger the shock catches up with the leading edge of the ejecta and breaks out at a radius of $R_{\text{bo}} = 2.4 \times 10^{11} \text{ cm} = 8 \text{ light-seconds}$. Thus, photons released during the cocoon shock breakout are only 2 s behind the gravitational waves released at the merger, thereby consistent with the delay between the merger and γ -rays observed by Fermi (3, 4). The breakout also takes place at a radius and velocity that is expected to produce a signal consistent with EM170817.

We end the simulation at $t = 15$ s when all the expansion is homologous and all the material moves ballistically. The emission after the breakout is calculated as a post-processing of the final snapshot of the hydrodynamical simulation, following a similar procedure to that described in (34). It contains two components: (i) diffusion of photons that were deposited by the shock that crossed the ejecta, which we call “cooling emission”, and (ii) radioactive decay of the elements that were synthesized in the ejecta, termed “macronova”. In short, for each time step in the observer’s frame we calculate first the radial optical depth from every radius to infinity along a radial path. We do that for different angles and we determine the trapping radius, $r_t(\theta)$, where the optical depth $\tau(r_t(\theta)) = c/v$. Above this radius, photons diffuse freely to the observer at infinity while below this radius they are trapped. This is an approximation since the outflow is not spherically symmetric. In a similar manner, we calculate for each angle the photospheric radius $r_{\text{ph}}(\theta)$ for which $\tau(r_{\text{ph}}(\theta)) = 1$. To obtain an approximated calculation that includes correction due to the mildly relativistic motion, we first calculate the luminosity in the comoving frame. The cooling emission luminosity in a comoving frame is determined by the diffusion of the rest frame energy flux at the trapping radius of the radiation that was carried by

the outflow from the last hydrodynamical snapshot. The macronova emission arises from the radioactive heating $\dot{\epsilon}$ generated by all the material above the trapping radius, $m(r > r_t)$, and is estimated at the rest frame of the photosphere as $\dot{\epsilon} = m(r > r_t)\epsilon_0 10^{10} \left(\frac{t}{1\text{d}}\right)^{-1.3} \text{ erg s}^{-1}$, where ϵ_0 is of order unity (129). We take $\epsilon_0 = 2$ during the first two days and reduce it to $\epsilon_0 = 1.5$ afterwards (116).

Next, we estimate the rest frame temperature at $r_{\text{ph}}(\theta)$ by taking the rest frame luminosity (the sum of cooling and macronova emission) in each direction and finding the radiation energy density at the photosphere assuming that the radiation is in thermal equilibrium and that the local radiation spectrum is a blackbody at this point. We assume that this blackbody radiation is emitted isotropically at the matter's rest frame of the photosphere. Having the rest frame luminosity and spectrum along each angle at every time in the explosion frame, we integrate the contribution from material at all angles for observers at different viewing angles at different observer times, by properly accounting for the Lorentz boost and the light travel time.

Finally, in order to find the ejecta optical depth at each time and place we need to estimate its opacity. For that we use tracers which mark material that is ejected initially (at $t = 0$) at different angles. By looking at the velocity distribution of the tracers at the end of the simulation we find that material that was ejected initially near the equator is associated with the slowest velocities ($v/c < 0.1$) while material that was ejected initially at high latitudes is associated with faster material. This is not surprising given that the energy of the jet was mostly deposited in high latitude material. Following (116) we adopt an opacity $\kappa = 10 \text{ cm}^2 \text{ g}^{-1}$ for material slower than $0.1c$, which is presumably dominated by neutron rich dynamical ejecta that contains Lanthanides, and $\kappa = 1.0 \text{ cm}^2 \text{ g}^{-1}$ for material that is faster than $0.1c$ which was presumably ejected from the disk and/or the massive neutron star that were formed after the merger and does not contain r-process elements from the second and third peaks.

Throughout the simulations we applied an ideal gas equation of state with an adiabatic

index of $4/3$ as appropriate for a radiation-dominated gas, and neglect gravity given that kinetic energy dominates the ejecta in the simulation domain. For the integration an Harten-Lax-van Leer (HLL) Riemann solver and a third order Runge Kutta time-stepping have been used. We employed a cylindrical grid with 1620×1600 cells. The grid is divided in three patches on the x -axis and two on the z -axis (parallel to the jet axis). The innermost patch on the x -axis is stretching from the origin to $x = 2 \times 10^8$ cm with 20 cells uniformly distributed, this patch makes sure the jet's nozzle contains enough cells. Most of the cocoon forms and experiences the mixing up to $x = 2 \times 10^{10}$ cm and $z = 2 \times 10^{10}$ cm. In this region we employ a resolution of 800 cells on each axis. Outside of these coordinates, the grid contains a uniform distribution of 800 additional cells in each axis up to $x = 4 \times 10^{11}$ cm and $z = 4 \times 10^{11}$ cm.

Early-time emission powered by an engine-driven wind

We proposed two options to explain bright and blue emission seen on the first day. Both options rely on radioactive heating (one involved mildly relativistic material and the other material with relatively low opacity) to power the emission. Here we suggest a third possibility: the release of internal energy that was deposited in the ejecta by an engine-driven wide-angle wind that lasted for ~ 20 s.

In the cocoon model that we presented above, the cooling emission fades within hours and does not contribute to the observed emission. The energy is deposited by the jet over a short duration when the ejecta radius is small. Then adiabatic losses cool the radiation by the time that the radiation is emitted. This can be shown using the following simple arguments. Assume that energy is deposited at radius R_0 in a mass M . This energy is deposited by a strong shock so about half of it is deposited in the form of radiation while the other half accelerates the mass to a velocity $v = \beta c$. The radiation is released at the time t_{rad} given in equation S12 at a radius $R_{\text{rad}} \approx vt_{\text{rad}}$ after adiabatic losses have reduced the internal energy to MvR_0/t_{rad} and

the luminosity is $L \sim MvR_0/t_{\text{rad}}^2$. Then using equation S12 for t_{rad} we find:

$$L \approx 6 \times 10^{40} \text{ erg s}^{-1} \kappa^{-1} \frac{R_0}{10^{10} \text{ cm}} \left(\frac{\beta}{0.2} \right)^2 \quad (\text{S10})$$

independent of the mass. We observed a luminosity of 10^{42} erg implying that in order to explain the early emission as shock cooling, the shock should hit the ejecta at a radius of $\sim 10^{11}$ cm. Since the ejecta propagates at a velocity that does not exceed $\sim 0.2c$ it should be shocked ~ 20 s after the merger. Such an option is plausible given that we know that in some sGRBs there is engine activity that releases energy comparable to that seen in the burst over a duration of ~ 100 s (36).

To verify our simple estimates we carried out a 1D numerical simulation with spherical symmetry (using the same code as in the main text, where the z -axis is now the spherical r -axis). We inject an engine-driven wind that lasts for 20 s and contains a total energy of 2×10^{51} erg into $0.05 M_\odot$ of cold ejecta which maintains a power-law density profile with index -1 , and expands homologously with an initial velocity of $0.1\text{--}0.2c$. We found that this can produce the observed emission during the first day for opacity $\kappa \approx 3 \text{ cm}^2 \text{ g}^{-1}$. We conclude that long-lasting engine-driven wind is another possible explanation for the bright, blue emission of EM170817 seen during the first day.

Early-time emission powered by free neutron decay

The observed emission during the first day is brighter, bluer and rises faster than predicted for the standard models of radioactive decay of r-process elements (25–28). It was suggested (130) that the decay of free neutrons may give rise to an early blue emission. We therefore examine if decay of free neutrons may have made a substantial contribution to the UV/optical emission observed during the first day.

Consider an outflow with a mass m_{-2} (in units of $10^{-2} M_\odot$), a typical velocity $\beta_{0.5}$ (in units of $0.5c$) and an initial free neutron fraction X_n . The evolution of internal energy confined to the

flow, E , can be estimated as:

$$\frac{dE}{dt} = \frac{E}{t} + L_h - L_{\text{rad}} \quad (\text{S11})$$

The first term takes into account adiabatic losses, the second heating term is due to neutron decay, $L_h = 6 \times 10^{45} m_{-2} X_n e^{(-t/900\text{s})} \text{ erg s}^{-1}$, and the cooling term L_{rad} accounts for radiative losses. The trapped radiation is released roughly at

$$t_{\text{rad}} \approx \left(\frac{\kappa m}{4\pi c v} \right)^{1/2} = 0.7 m_{-2}^{0.5} \kappa^{0.5} \beta_{0.5}^{-0.5} \text{ day}, \quad (\text{S12})$$

where opacity κ is in $\text{cm}^2 \text{ g}^{-1}$. Up to $t \ll t_{\text{rad}}$ equation S11 can be integrated neglecting radiative losses. For $900 \text{ s} \ll t \ll t_{\text{rad}}$ this integration yields $E = 6 \times 10^{46} m_{-2} X_n t_d^{-1} \text{ erg}$, where t_d is time in days. The trapped radiation is radiated at t_{rad} with a peak luminosity that is roughly $L_{\text{peak}} \approx E/t_{\text{rad}}$.

$$L_{\text{peak}} \approx \frac{E(t_{\text{rad}})}{t_{\text{rad}}} \approx 2 \times 10^{42} X_n \kappa^{-1} \beta_{0.5} \text{ erg s}^{-1} \quad (\text{S13})$$

This luminosity is independent of m_{-2} . The observed luminosity during the first day implies that for $\kappa = 1 \text{ cm}^2 \text{ g}^{-1}$, X_n is 0.5 and the ejecta must be at least $\sim 0.01 M_\odot$ of almost pure free neutrons. For larger κ neutrons cannot produce the observed signal while lower κ reduces the neutron fraction, while increasing the total mass by the same factor (to match t_{rad}), so an unrealistically high mass of $\sim 0.01 M_\odot$ of free neutrons is always needed to explain the observations from the first day.

Rates

EM170817-like events in the Palomar Transient Factory database

The Palomar Transient Factory (PTF; (131)) and intermediate Palomar Transient Factory (iPTF; (132, 133)) databases keep track of every detection with significance greater than $5\text{-}\sigma$ on every image subtraction performed during 2009 to 2017. This facilitates our ability to calculate the rates of a variety of astrophysical events in hindsight. We determined the efficiency of every image subtraction for a transient of a given magnitude superimposed on a galaxy of a given surface brightness for the PTF survey over the time frame of 2010 January through 2012 December (134). By coupling these efficiencies with a Monte Carlo simulation of a particular transient event, we can calculate a rate based on comparison to the observed number of such transients found during the survey or, if no such events were found, we can provide an upper limit on this rate.

We used these efficiencies, coupled with the lightcurve for EM170817 to calculate the rate in the following manner. First we performed a search in R -band for all transients resembling EM170817. We only performed the search within the search radius of the CLU (Census of the Local Universe; (8)) galaxy catalog within 200 Mpc as defined in (80). We required 3 detections above our machine-learning threshold for a real source (135) found within a 10-day time frame with at least one non-detection both the week prior to the event and the week after the event. No other significant detections in the database were allowed at any time during the survey.

The result of this search yielded 2 potential candidate events, one of which is almost certainly a heretofore unreported nova in NGC 253. The other event, similar in absolute brightness and decline rate as EM170817, may be a similar event but may be a false positive. For now we will assume there are no positive detections of such events in PTF and proceed to calculate an upper limit for this rate.

From here we simulated, through a Monte Carlo, the lightcurves of EM170817 as seen in

our survey and if they would meet the required detection thresholds as defined above.

From here we simulated the lightcurves of EM170817 as seen in our survey via a Monte Carlo, asking the question at each point in our past observing schedule whether or not the transient would be seen above our real-bogus threshold based upon the sky conditions, background host galaxy light, seeing, and other factors as found through our efficiency studies. Then we evaluated if enough data points met the required 3 detections above our real-bogus threshold, found within a 10-day time-frame with at least one non-detection both the week prior and post the event. If so, it was counted as a positive detection towards the relative rate. The result of this simulation is an event rate of $320 \text{ Gpc}^{-3} \text{ yr}^{-1}$ and a $3\text{-}\sigma$ upper limit of $800 \text{ Gpc}^{-3} \text{ yr}^{-1}$. Relating this back to the optical counterparts of NS-NS mergers, the major uncertainty is the luminosity function in the R -band of such events. If the typical NS-NS merger is 50% fainter, the upper limit on such events nearly doubles to over $1600 \text{ Gpc}^{-3} \text{ yr}^{-1}$.

A similar search was carried out in the iPTF database yielding no corresponding detections using the techniques reported in (136), which means that the rate described above is conservative.

Implications for rates based on r-process abundances

Here we discuss the relation of GW/EM170817 to the origin of r-process elements in the Universe. There are three peaks in atomic mass seen in r-process abundances (figure S10), near atomic mass number A of 80, 130, and 195. The mass of the ejected r-process elements is estimated to be at least $\sim 0.05M_{\odot}$ in order to explain the observed light curves and spectra. The bright emission at early times suggests that the Lanthanide-free material with a mass of $> 0.02M_{\odot}$ is ejected (with $A < 140$; see figure S10). Given the ejecta mass and merger rate deduced above, we can test the hypothesis that mergers produced all the r-process elements heavier than a minimal atomic mass number, $A_{\min} > 70$, in the Milky Way. The value of A_{\min}

for the merger ejecta depends on the stiffness of the neutron star equation of state (*137, 138*) and the lifetime of the remnant massive neutron star (*139*), see also recent studies on the nucleosynthesis in the merger ejecta (*140, 141*). Roughly 80% of r-process elements are around the first r-process peak at A of 80 (figure S10). Therefore the rate estimate from the Galactic r-process abundance is quite sensitive to the choice of A_{\min} . Assuming that the solar r-process abundance is the typical of the Milky Way stars, we estimate the volumetric rate (*142*):

$$R \sim \begin{cases} 500 \left(\frac{M_{\text{ej}}}{0.05 M_{\odot}} \right)^{-1} \text{ Gpc}^{-3} \text{ yr}^{-1} & (A_{\min} = 70), \\ 100 \left(\frac{M_{\text{ej}}}{0.05 M_{\odot}} \right)^{-1} \text{ Gpc}^{-3} \text{ yr}^{-1} & (A_{\min} = 90), \end{cases} \quad (\text{S14})$$

where we use the number density of galaxies of $\approx 0.01 \text{ Mpc}^{-3}$. The former corresponds to all the r-process elements being produced by mergers and the latter corresponds to only the heavier r-process elements being produced without the first peak. The large event rate and ejecta mass inferred from GW/EM170817 suggest that the majority of r-process elements are produced by mergers. However, the abundance patterns of the first-peak elements of extremely metal poor stars do not agree with each other (*143*). This suggests that more than one type of astrophysical phenomenon may produce these elements or there is variation in the composition and amount of the r-process ejecta of neutron star mergers.

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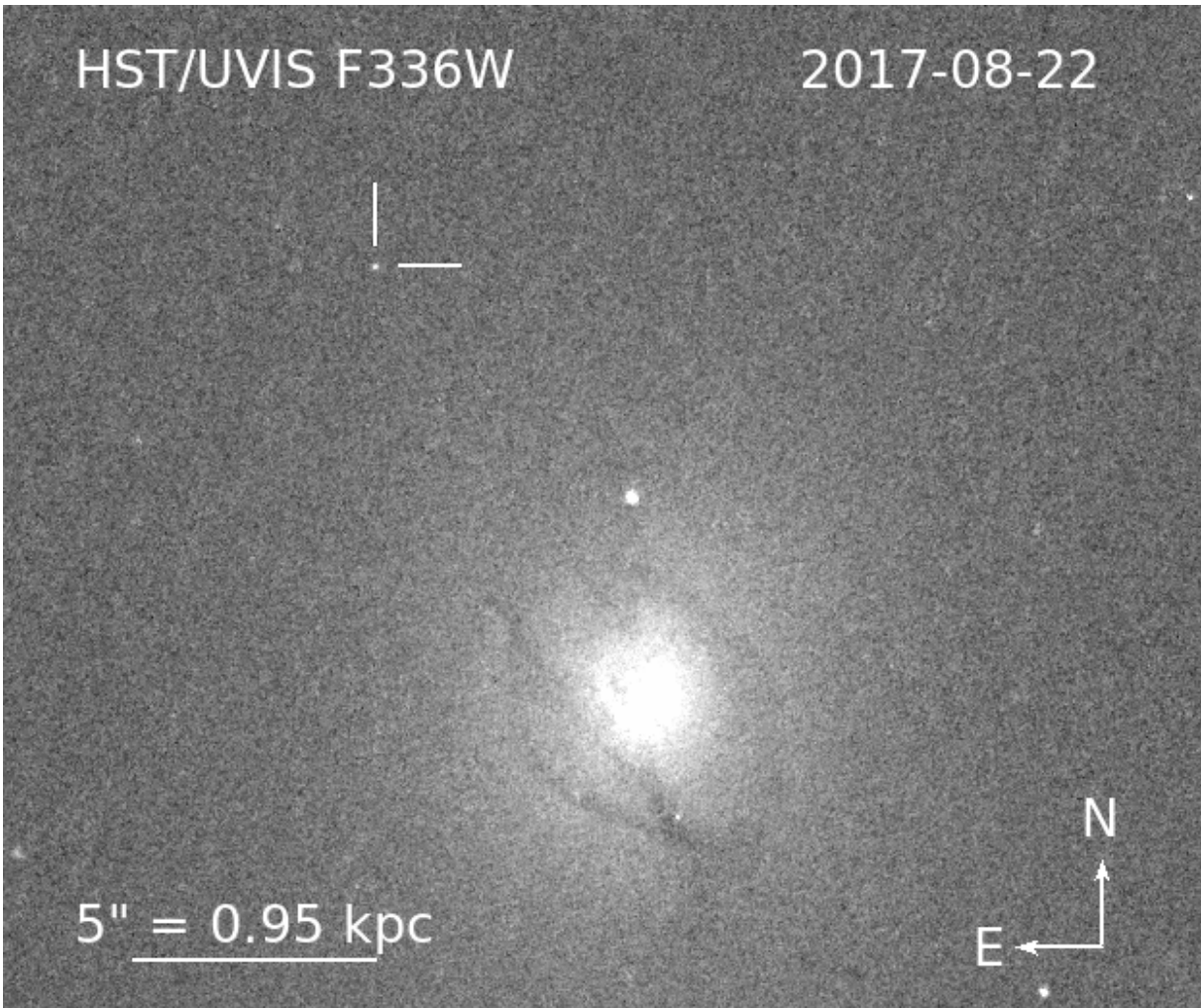


Figure S1: *Hubble Space Telescope* WFC3/F336W ultraviolet image of EM170817 and NGC 4993, taken 2017 August 22. North is up, east is the to left, and a 5'' scale-bar is indicated. The position of the transient is shown with tick marks. Dust lanes are visible toward the center of NGC 4993.

Table S1: New and archival ultraviolet, optical, and near-infrared photometry of EM170817. For each observation we give the observation date, time since GW170817, telescope, instrument, filter, and AB magnitude. Upper limits are all at 5- σ confidence. We did not use photometry from several telescopes where the results reported in circulars were uncertain (152–155).

Observation Date (UTC)	Δt (d)	Telescope	Instrument	Filter	AB Magnitude	Reference
2017-08-17 23:31	0.45	Swope	directCCD	<i>i</i>	17.33 ± 0.10	(14, 156, 157)
2017-08-18 00:01	0.47	PROMPT5	CCD	<i>R</i>	17.52 ± 0.20	(158, 159)
2017-08-18 00:04	0.47	CTIO	DECam	<i>i</i>	17.50 ± 0.10	(160, 161)
2017-08-18 00:04	0.47	CTIO	DECam	<i>z</i>	17.50 ± 0.10	(160, 161)
2017-08-18 00:10	0.48	ESO-VISTA	VIRCAM	<i>J</i>	18.42 ± 0.10	(162)
2017-08-18 00:15	0.48	Magellan-Clay	MEGACAM	<i>g</i>	17.20 ± 0.10	(157, 163)
2017-08-18 01:30	0.53	Gemini-S	FLAMINGOS-2	<i>K_s</i>	18.42 ± 0.04	this paper
2017-08-18 03:44	0.63	<i>Swift</i>	UVOT	UVM2	21.32 ± 0.22	(15)
2017-08-18 03:54	0.63	<i>Swift</i>	UVOT	UVW1	19.62 ± 0.11	(15)
2017-08-18 04:01	0.64	<i>Swift</i>	UVOT	<i>U</i>	18.23 ± 0.08	(15)
2017-08-18 04:07	0.64	<i>Swift</i>	UVOT	UVW2	21.48 ± 0.25	(15)
2017-08-18 05:33	0.70	Pan-STARRS	GPC1	<i>y</i>	17.28 ± 0.13	(164, 165)
2017-08-18 05:33	0.70	Pan-STARRS	GPC1	<i>z</i>	17.31 ± 0.09	(164, 165)
2017-08-18 05:34	0.70	Pan-STARRS	GPC1	<i>i</i>	17.23 ± 0.10	(164, 165)
2017-08-18 05:35	0.70	Pan-STARRS	GPC1	<i>y</i>	17.47 ± 0.16	(164, 165)
2017-08-18 05:36	0.71	Pan-STARRS	GPC1	<i>z</i>	17.21 ± 0.08	(164, 165)
2017-08-18 05:37	0.71	Pan-STARRS	GPC1	<i>i</i>	17.26 ± 0.08	(164, 165)
2017-08-18 05:40	0.71	Subaru	HSC	<i>z</i>	17.30 ± 0.10	(166)
2017-08-18 09:42	0.88	SSO	CCD	<i>g</i>	17.50 ± 0.20	(167)
2017-08-18 13:39	1.04	<i>Swift</i>	UVOT	UVW1	20.36 ± 0.21	(15)
2017-08-18 13:43	1.04	<i>Swift</i>	UVOT	<i>U</i>	19.05 ± 0.16	(15)
2017-08-18 13:48	1.05	<i>Swift</i>	UVOT	UVW2	> 21.19	(15)
2017-08-18 14:11	1.06	AST3-2	CCD	<i>g</i>	18.15 ± 0.10	(168, 169)
2017-08-18 14:15	1.07	<i>Swift</i>	UVOT	UVM2	> 21.25	(15)
2017-08-18 17:17	1.19	KMTNet	18KCCD	<i>V</i>	17.83 ± 0.10	(17, 170)
2017-08-18 17:17	1.19	KMTNet	18KCCD	<i>I</i>	17.75 ± 0.10	(17, 170)
2017-08-18 17:17	1.19	KMTNet	18KCCD	<i>R</i>	17.62 ± 0.10	(17, 170)
2017-08-18 17:17	1.19	MASTER-II	NA	<i>R</i>	17.42 ± 0.20	(171, 172)
2017-08-18 17:34	1.20	MASTER-II	NA	<i>B</i>	18.42 ± 0.10	(171, 172)
2017-08-18 20:42	1.33	NOT	NOTCam	<i>J</i>	17.13 ± 0.11	(173)
2017-08-18 20:42	1.33	NOT	NOTCam	<i>K_s</i>	17.70 ± 0.25	(173)
2017-08-18 23:45	1.46	KMTNet	18KCCD	<i>R</i>	17.82 ± 0.10	(17, 170)
2017-08-18 23:46	1.46	KMTNet	18KCCD	<i>I</i>	17.85 ± 0.10	(17, 170)
2017-08-18 23:46	1.46	KMTNet	18KCCD	<i>V</i>	18.33 ± 0.10	(17, 170)
2017-08-18 23:59	1.47	PROMPT5	CCD	<i>R</i>	18.22 ± 0.06	(159, 174)
2017-08-19 00:44	1.50	<i>Swift</i>	UVOT	<i>U</i>	> 19.50	(15)
2017-08-19 00:50	1.51	<i>Swift</i>	UVOT	UVW2	> 21.53	(15)
2017-08-19 01:15	1.52	<i>Swift</i>	72UVOT	UVM2	> 21.71	(15)

Table S1: New and archival ultraviolet, optical, and near-infrared photometry of EM170817 (continued).

Observation Date (UTC)	Δt (d)	Telescope	Instrument	Filter	AB Magnitude	Reference
2017-08-19 01:23	1.53	<i>Swift</i>	UVOT	UVW1	> 20.86	(15)
2017-08-19 01:55	1.55	Swope	directCCD	<i>B</i>	18.70 ± 0.10	(14, 157, 175)
2017-08-19 01:55	1.55	Swope	directCCD	<i>V</i>	18.14 ± 0.10	(14, 157, 175)
2017-08-19 01:55	1.55	Swope	directCCD	<i>i</i>	17.43 ± 0.10	(14, 157, 175)
2017-08-19 05:39	1.71	Subaru	HSC	<i>z</i>	17.80 ± 0.10	(176)
2017-08-19 05:46	1.71	Pan-STARRS	GPC1	<i>i</i>	17.91 ± 0.05	(165, 177)
2017-08-19 05:46	1.71	Pan-STARRS	GPC1	<i>y</i>	17.59 ± 0.07	(165, 177)
2017-08-19 05:46	1.71	Pan-STARRS	GPC1	<i>z</i>	17.80 ± 0.05	(165, 177)
2017-08-19 10:59	1.93	Zadko	AndorIKON-L	<i>r</i>	18.46 ± 0.17	(169, 178)
2017-08-19 14:09	2.06	<i>Swift</i>	UVOT	<i>U</i>	> 21.02	(15)
2017-08-19 14:17	2.07	<i>Swift</i>	UVOT	UVW2	> 21.55	(15)
2017-08-19 14:25	2.07	<i>Swift</i>	UVOT	UVM2	> 21.59	(15)
2017-08-19 14:33	2.08	<i>Swift</i>	UVOT	UVW1	> 21.57	(15)
2017-08-19 17:17	2.19	KMTNet	18KCCD	<i>R</i>	18.52 ± 0.10	(17, 170)
2017-08-19 17:17	2.19	KMTNet	18KCCD	<i>V</i>	19.43 ± 0.10	(17, 170)
2017-08-19 17:17	2.19	KMTNet	18KCCD	<i>I</i>	18.35 ± 0.10	(17, 170)
2017-08-19 17:53	2.22	MASTER-II	NA	<i>R</i>	18.42 ± 0.30	(171, 172)
2017-08-19 23:23	2.45	CTIO	DECam	<i>i</i>	17.80 ± 0.10	(161, 179, 180)
2017-08-19 23:23	2.45	CTIO	DECam	<i>z</i>	17.60 ± 0.10	(161, 179, 180)
2017-08-19 23:31	2.45	KMTNet	18KCCD	<i>R</i>	18.62 ± 0.10	(17, 170)
2017-08-19 23:31	2.45	KMTNet	18KCCD	<i>I</i>	18.65 ± 0.10	(17, 170)
2017-08-19 23:31	2.45	KMTNet	18KCCD	<i>V</i>	19.83 ± 0.10	(17, 170)
2017-08-19 23:50	2.46	PROMPT5	CCD	<i>r</i>	18.96 ± 0.10	(159, 181)
2017-08-20 00:19	2.49	Gemini-S	FLAMINGOS-2	<i>K_s</i>	17.60 ± 0.04	this paper
2017-08-20 00:27	2.49	Gemini-S	FLAMINGOS-2	<i>J</i>	17.76 ± 0.02	this paper
2017-08-20 05:46	2.71	Pan-STARRS	GPC1	<i>y</i>	18.08 ± 0.07	(165, 182)
2017-08-20 05:46	2.71	Pan-STARRS	GPC1	<i>i</i>	18.47 ± 0.08	(165, 182)
2017-08-20 05:46	2.71	Pan-STARRS	GPC1	<i>z</i>	18.31 ± 0.06	(165, 182)
2017-08-20 11:14	2.94	Zadko	AndorIKON-L	<i>r</i>	19.18 ± 0.12	(169, 178)
2017-08-20 11:47	2.96	<i>Swift</i>	UVOT	UVW1	> 22.18	(15)
2017-08-20 13:08	3.02	<i>Swift</i>	UVOT	<i>U</i>	> 21.87	(15)
2017-08-20 13:11	3.02	<i>Swift</i>	UVOT	<i>B</i>	> 19.82	(15)
2017-08-20 13:17	3.03	<i>Swift</i>	UVOT	UVW2	> 22.76	(15)
2017-08-20 13:25	3.03	<i>Swift</i>	UVOT	<i>V</i>	> 19.04	(15)
2017-08-20 15:11	3.10	<i>Swift</i>	UVOT	UVM2	> 23.29	(15)
2017-08-21 00:35	3.50	Gemini-S	FLAMINGOS-2	<i>J</i>	17.93 ± 0.06	this paper
2017-08-21 00:38	3.50	Gemini-S	FLAMINGOS-2	<i>H</i>	17.72 ± 0.04	this paper
2017-08-21 00:40	3.50	Gemini-S	FLAMINGOS-2	<i>K_s</i>	17.61 ± 0.06	this paper

Table S1: New and archival ultraviolet, optical, and near-infrared photometry of EM170817 (continued).

Observation Date (UTC)	Δt (d)	Telescope	Instrument	Filter	AB Magnitude	Reference
2017-08-21 05:31	3.70	Pan-STARRS	GPC1	y	> 18.00	(165, 183)
2017-08-21 05:46	3.71	Pan-STARRS	GPC1	z	18.27 ± 0.33	(165, 183)
2017-08-21 05:46	3.71	Pan-STARRS	GPC1	i	> 18.50	(165, 183)
2017-08-21 09:30	3.87	Zadko	AndorIKON-L	r	19.86 ± 0.21	(169, 178)
2017-08-22 01:00	4.51	Gemini-S	FLAMINGOS-2	K_s	17.72 ± 0.09	this paper
2017-08-22 01:03	4.52	Gemini-S	FLAMINGOS-2	J	18.15 ± 0.06	this paper
2017-08-22 01:06	4.52	Gemini-S	FLAMINGOS-2	H	18.02 ± 0.07	this paper
2017-08-22 09:43	4.88	<i>Swift</i>	UVOT	UVW1	> 22.14	(15)
2017-08-22 11:43	4.96	Zadko	AndorIKON-L	r	20.20 ± 0.23	(169, 178)
2017-08-22 20:19	5.32	<i>HST</i>	WFC3/UVIS	F336W	24.97 ± 0.11	this paper
2017-08-22 20:28	5.32	<i>HST</i>	WFC3/UVIS	F336W	25.05 ± 0.11	this paper
2017-08-22 21:01	5.35	<i>HST</i>	WFC3/UVIS	F336W	25.18 ± 0.11	this paper
2017-08-22 23:23	5.45	ESO-VST	OMEGACAM	i	21.31 ± 0.10	(184)
2017-08-22 23:23	5.45	ESO-VST	OMEGACAM	r	22.43 ± 0.10	(184)
2017-08-22 23:23	5.45	ESO-VST	OMEGACAM	g	23.27 ± 0.10	(184)
2017-08-23 08:04	5.81	<i>Swift</i>	UVOT	U	> 20.74	(15)
2017-08-23 08:05	5.81	<i>Swift</i>	UVOT	B	> 19.94	(15)
2017-08-23 08:07	5.81	<i>Swift</i>	UVOT	UVW2	> 23.03	(15)
2017-08-23 08:09	5.81	<i>Swift</i>	UVOT	V	> 18.91	(15)
2017-08-23 08:11	5.81	<i>Swift</i>	UVOT	UVM2	> 22.66	(15)
2017-08-23 11:48	5.96	Zadko	AndorIKON-L	r	> 20.60	(169, 178)
2017-08-23 17:22	6.20	IRSF	SIRIUS	H	18.60 ± 0.18	this paper
2017-08-23 17:22	6.20	IRSF	SIRIUS	K_s	18.01 ± 0.10	this paper
2017-08-23 17:22	6.20	IRSF	SIRIUS	J	18.65 ± 0.19	this paper
2017-08-23 23:35	6.45	VLT	VISIR	$J8.9$	> 8.26	this paper
2017-08-24 11:55	6.97	Zadko	AndorIKON-L	r	> 20.60	(169, 178)
2017-08-24 16:51	7.17	IRSF	SIRIUS	J	18.95 ± 0.32	this paper
2017-08-24 16:51	7.17	IRSF	SIRIUS	H	18.53 ± 0.17	this paper
2017-08-24 16:51	7.17	IRSF	SIRIUS	K_s	18.02 ± 0.12	this paper
2017-08-24 23:20	7.44	CTIO1.3m	ANDICAM	K	18.06 ± 0.17	this paper
2017-08-25 11:52	7.97	Zadko	AndorIKON-L	r	> 20.60	(169, 178)
2017-08-25 16:42	8.17	<i>Swift</i>	UVOT	UVW1	> 22.51	(15)
2017-08-25 23:29	8.45	CTIO1.3m	ANDICAM	K	18.44 ± 0.18	this paper
2017-08-26 16:57	9.18	IRSF	SIRIUS	H	18.83 ± 0.23	this paper
2017-08-26 16:57	9.18	IRSF	SIRIUS	K_s	18.25 ± 0.21	this paper
2017-08-26 16:57	9.18	IRSF	SIRIUS	J	> 18.87	this paper
2017-08-26 22:56	9.43	Gemini-S	FLAMINGOS-2	K_s	18.50 ± 0.08	this paper
2017-08-26 23:01	9.43	Gemini-S	FLAMINGOS-2	J	20.57 ± 0.20	this paper

Table S1: New and archival ultraviolet, optical, and near-infrared photometry of EM170817 (continued).

Observation Date (UTC)	Δt (d)	Telescope	Instrument	Filter	AB Magnitude	Reference
2017-08-26 23:05	9.43	Gemini-S	FLAMINGOS-2	<i>H</i>	19.68 ± 0.08	this paper
2017-08-26 23:21	9.44	CTIO1.3m	ANDICAM	<i>K</i>	18.43 ± 0.17	this paper
2017-08-27 02:15	9.57	APO	NICFPS	<i>K_s</i>	> 17.99	this paper
2017-08-27 02:49	9.59	Palomar5m	WHIRC	<i>K_s</i>	> 17.64	this paper
2017-08-27 23:07	10.43	Gemini-S	FLAMINGOS-2	<i>K_s</i>	18.77 ± 0.07	this paper
2017-08-27 23:10	10.44	Gemini-S	FLAMINGOS-2	<i>H</i>	19.63 ± 0.08	this paper
2017-08-27 23:16	10.44	Gemini-S	FLAMINGOS-2	<i>J</i>	21.33 ± 0.30	this paper
2017-08-27 23:18	10.44	CTIO1.3m	ANDICAM	<i>K</i>	18.91 ± 0.19	this paper
2017-08-28 16:40	11.17	<i>Swift</i>	UVOT	<i>B</i>	> 20.48	(15)
2017-08-28 16:44	11.17	<i>Swift</i>	UVOT	UVW2	> 24.32	(15)
2017-08-28 16:47	11.17	<i>Swift</i>	UVOT	<i>V</i>	> 20.07	(15)
2017-08-28 16:50	11.17	<i>Swift</i>	UVOT	UVM2	> 23.29	(15)
2017-08-28 16:52	11.17	IRSF	SIRIUS	<i>J</i>	> 18.37	this paper
2017-08-28 16:52	11.17	IRSF	SIRIUS	<i>K_s</i>	> 18.48	this paper
2017-08-28 16:52	11.17	IRSF	SIRIUS	<i>H</i>	> 18.43	this paper
2017-08-28 17:21	11.20	<i>Swift</i>	UVOT	<i>U</i>	> 21.44	(15)
2017-08-28 23:17	11.44	CTIO1.3m	ANDICAM	<i>K</i>	> 19.11	this paper
2017-08-28 23:35	11.45	Gemini-S	FLAMINGOS-2	<i>K_s</i>	19.41 ± 0.09	this paper
2017-08-28 23:40	11.46	Gemini-S	FLAMINGOS-2	<i>H</i>	> 20.63	this paper
2017-08-28 23:45	11.46	Gemini-S	FLAMINGOS-2	<i>J</i>	> 21.07	this paper
2017-08-29 00:36	11.50	<i>HST</i>	WFC3/UVIS	F225W	> 26.04	this paper
2017-08-29 00:36	11.50	<i>HST</i>	WFC3/UVIS	F336W	> 26.37	this paper
2017-08-29 00:36	11.50	<i>HST</i>	WFC3/UVIS	F275W	> 26.13	this paper
2017-08-29 10:44	11.92	<i>Swift</i>	UVOT	UVW1	> 22.26	(15)
2017-08-29 23:10	12.44	Gemini-S	FLAMINGOS-2	<i>K_s</i>	19.44 ± 0.08	this paper
2017-08-29 23:23	12.45	Gemini-S	FLAMINGOS-2	<i>H</i>	20.99 ± 0.21	this paper
2017-08-29 23:41	12.46	Gemini-S	FLAMINGOS-2	<i>J</i>	> 21.55	this paper
2017-08-30 23:01	13.43	Gemini-S	FLAMINGOS-2	<i>K_s</i>	19.84 ± 0.09	this paper
2017-08-30 23:29	13.45	Gemini-S	FLAMINGOS-2	<i>H</i>	21.48 ± 0.30	this paper
2017-08-30 23:43	13.46	Gemini-S	FLAMINGOS-2	<i>J</i>	> 21.94	this paper
2017-08-31 23:03	14.43	Gemini-S	FLAMINGOS-2	<i>K_s</i>	20.06 ± 0.10	this paper
2017-08-31 23:18	14.44	VLT	VISIR	<i>J8.9</i>	> 7.74	this paper
2017-08-31 23:50	14.47	Gemini-S	FLAMINGOS-2	<i>H</i>	21.63 ± 0.36	this paper
2017-09-01 00:18	14.48	Gemini-S	GMOS	<i>i</i>	> 23.20	this paper
2017-09-01 23:18	15.44	VLT	VISIR	<i>J8.9</i>	> 7.57	this paper
2017-09-01 23:24	15.45	Gemini-S	FLAMINGOS-2	<i>K_s</i>	20.43 ± 0.13	this paper
2017-09-02 00:46	15.50	Gemini-S	GMOS	<i>i</i>	> 23.40	this paper
2017-09-02 23:22	16.45	Gemini-S	FLAMINGOS-2	<i>K_s</i>	20.95 ± 0.18	this paper

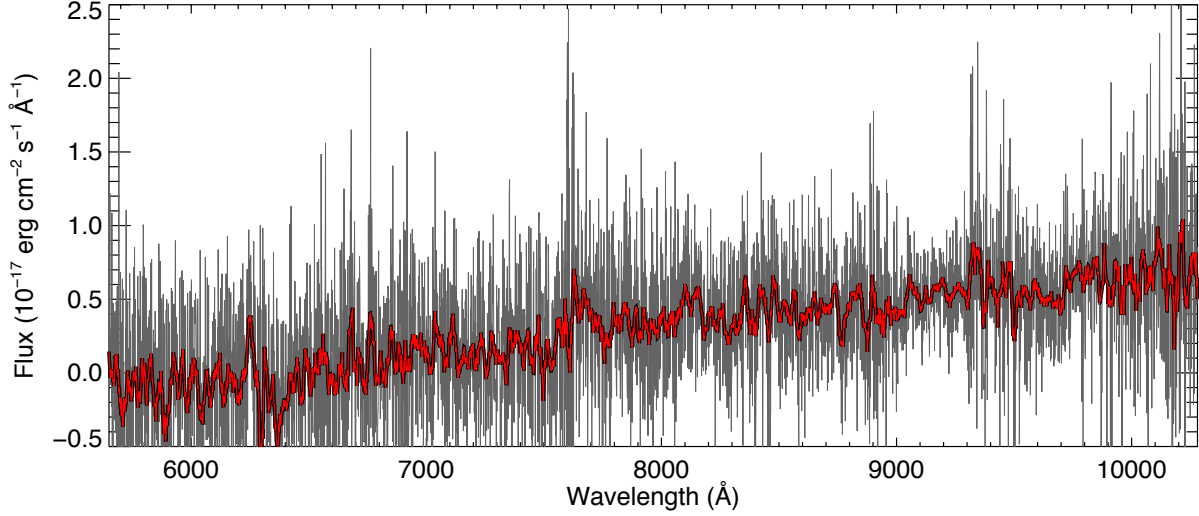


Figure S2: Optical spectrum of EM170817 taken 2017 August 25 with the Low Resolution Imaging Spectrometer on Keck I. The measured spectrum is shown in gray, and a version smoothed with a kernel of width 20 Å is shown in red. EM170817 was already quite faint at this time and no unambiguous features are evident.

Table S1: New and archival ultraviolet, optical, and near-infrared photometry of EM170817 (continued).

Observation Date (UTC)	Δt (d)	Telescope	Instrument	Filter	AB Magnitude	Reference
2017-09-03 00:03	16.47	Gemini-S	GMOS	<i>r</i>	> 21.18	this paper
2017-09-03 23:36	17.46	Gemini-S	FLAMINGOS-2	K_s	> 19.92	this paper
2017-09-04 00:16	17.48	Gemini-S	GMOS	<i>r</i>	> 21.98	this paper
2017-09-04 23:28	18.45	Gemini-S	FLAMINGOS-2	K_s	21.04 ± 0.09	this paper
2017-09-05 00:03	18.47	Gemini-S	GMOS	<i>i</i>	> 21.90	this paper
2017-09-05 23:48	19.46	Gemini-S	FLAMINGOS-2	K_s	21.23 ± 0.37	this paper
2017-09-06 23:30	20.45	Gemini-S	FLAMINGOS-2	<i>H</i>	> 21.22	this paper
2017-09-06 23:33	20.45	VLT	VISIR	$J8.9$	> 7.42	this paper
2017-09-07 23:39	21.46	Gemini-S	FLAMINGOS-2	K_s	> 21.48	this paper
2017-09-11 23:39	25.46	Gemini-S	FLAMINGOS-2	<i>J</i>	> 20.21	this paper
2017-09-14 23:14	28.44	Gemini-S	FLAMINGOS-2	K_s	> 19.96	this paper
2017-09-15 23:19	29.44	Gemini-S	FLAMINGOS-2	K_s	> 20.60	this paper

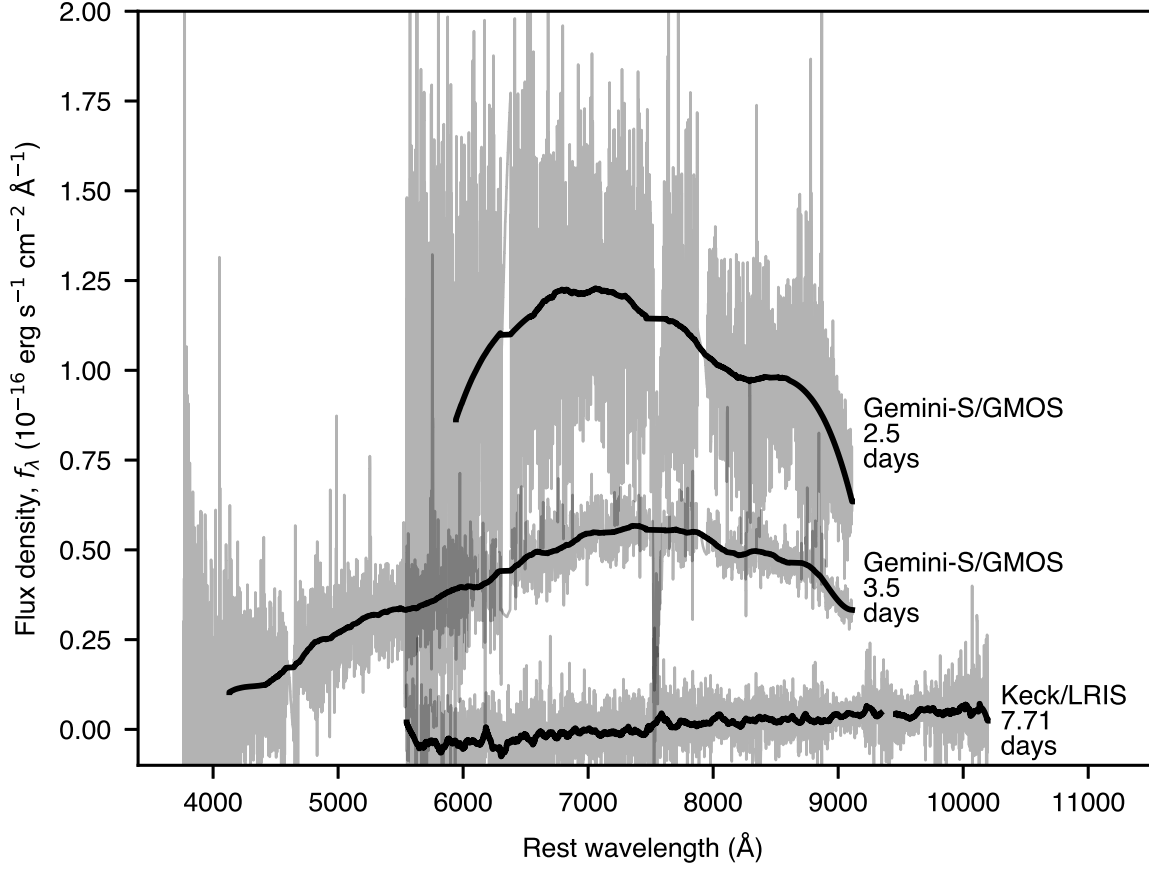


Figure S3: Optical spectral sequence of EM170817 including the Gemini-S/GMOS spectra from 2.5 and 3.5 days and the Keck/LRIS spectrum from 7.7 days. The measured spectra are shown in gray, and versions smoothed with a Savitsky-Golay filter are shown in black.

Table S2: Optical and near-IR spectroscopic observations of EM170817. For each observation we give the observation date, the time since GW170817, the telescope, instrument, exposure time, approximate wavelength range, and spectral resolving power.

Observation Date (UTC)	Δt (days)	Telescope	Instrument	Exposure (s)	Wavelength Range (\AA)	$\lambda/\Delta\lambda$
2017-08-20 01:08	2.52	Gemini-S	GMOS	2×300	6000–9000	1900
2017-08-21 00:15	3.48	Gemini-S	GMOS	4×360	3800–9200	1700
2017-08-22 00:21	4.49	Gemini-S	FLAMINGOS-2	8×150	12980–25070	600
2017-08-22 00:47	4.50	Gemini-S	FLAMINGOS-2	6×150	9840–18020	600
2017-08-25 05:45	7.71	Keck I	LRIS	$300 + 2 \times 600$	2000–10300	1000
2017-08-29 00:23	11.49	Gemini-S	FLAMINGOS-2	16×150	12980–25070	600

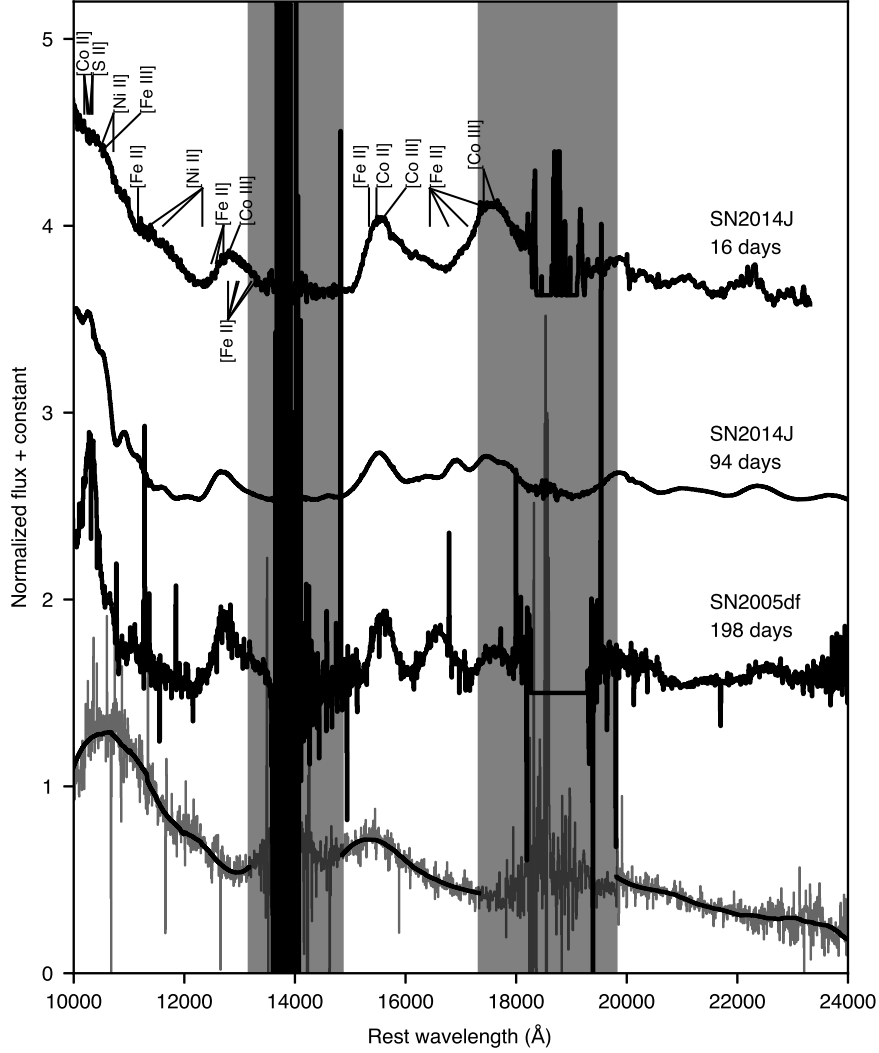


Figure S4: Near-infrared spectrum of EM170817 at $t = 4.5$ days post merger is shown at the bottom, along with the spectra of the type Ia SN 2014J at 16 and 94 days post maximum (144), and the type Ia SN 2005df at 198 days post maximum (145). Each spectrum is normalized to the flux between 10000–10500 Å and shifted up from the one below for clarity. The spectrum of EM170817 was corrected for Milky Way reddening assuming $E(B - V) = 0.1$ and a standard $R_V = 3.1$ extinction law (146), and smoothed using a Savitzky–Golay filter to clearly show the prominent, broad spectral features at ~ 10600 and 15000 Å. The unfiltered data are shown in gray. Regions of low S/N due to the strong telluric absorption features between the J , H , and K spectral windows are indicated by the vertical, gray bars. We label several transitions of Fe-peak elements on the top spectrum of SN 2014J. While qualitatively similar, the broad Fe-peak features characteristic of SNe Ia are inconsistent with the features observed in the spectrum of EM170817.

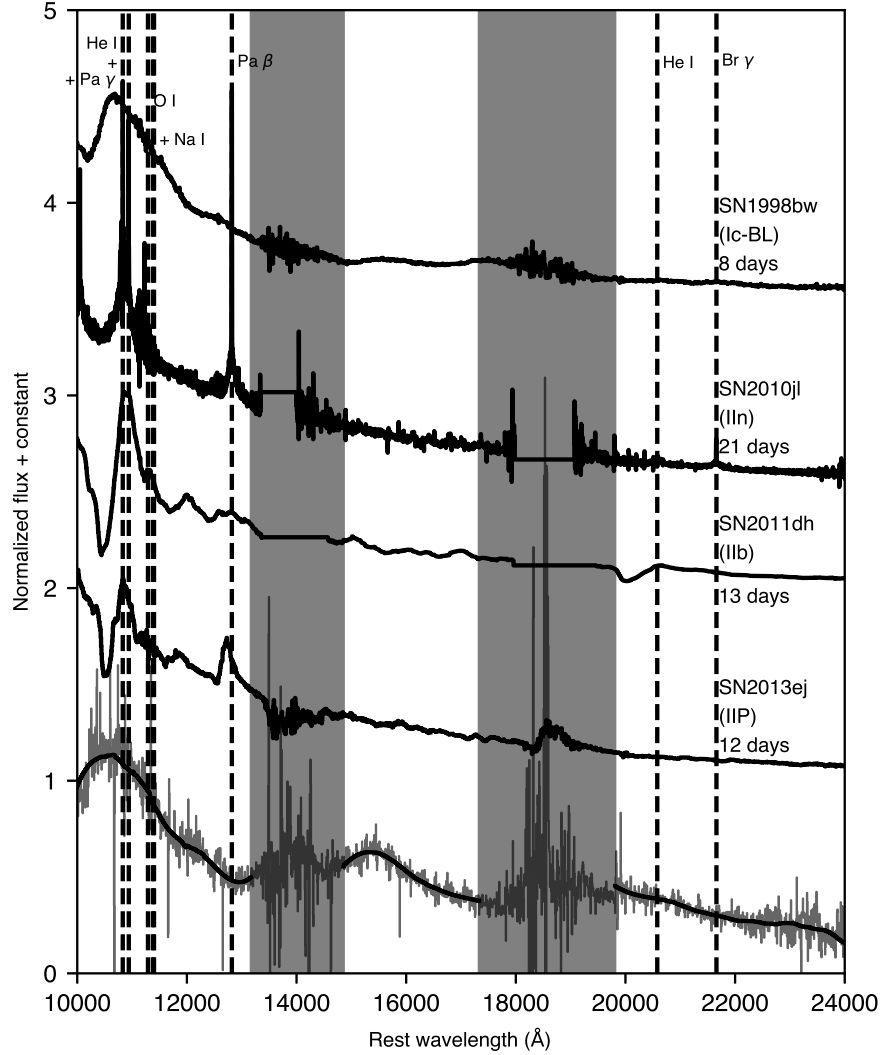


Figure S5: Near-infrared spectrum of EM170817 at $t = 4.5$ days post merger is shown at the bottom, along with the spectra of the type IIP SN 2013ej at 12 days (*147*), the type IIb SN 2011dh at 13 days (*148*), the type IIn SN 2010jl at 21 days (*149*), and the broad-lined type Ic (Ic-BL) SN 1998bw at 8 days post maximum (*150*). The spectra of EM170817 are presented as in figure S4. We label several transitions commonly identified in the spectra of core-collapse SNe with vertical, dashed lines.

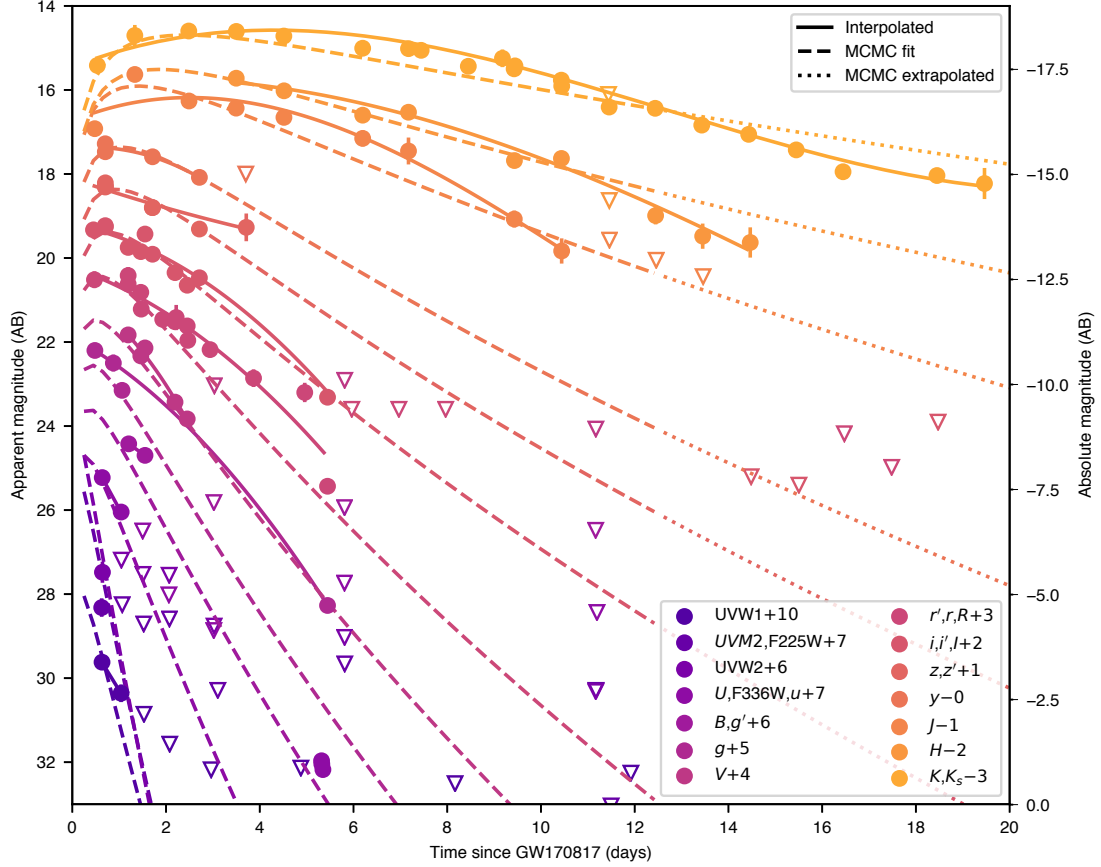


Figure S6: Multiwavelength lightcurve based on the ultraviolet/optical/infrared photometry of EM170817. The data are our assembled photometry (Table S1) plotted as AB magnitude vs. time since GW170817, with open triangles indicating 5σ upper limits, colored by wavelength. We plot both apparent magnitude and absolute magnitudes assuming distance of 40 Mpc. We illustrate both methods of blackbody fitting used here: the solid curves are the low-order polynomial functions used at each wavelength to fit a separate absorbed blackbody at every epoch, while the dashed curves are the evolving absorbed blackbodies fit simultaneously with a Markov-Chain Monte Carlo (MCMC) algorithm (the dotted portions are extrapolations). Filters with similar wavelengths (roughly within 300 \AA) have been grouped together for clarity, and some filters have been omitted.

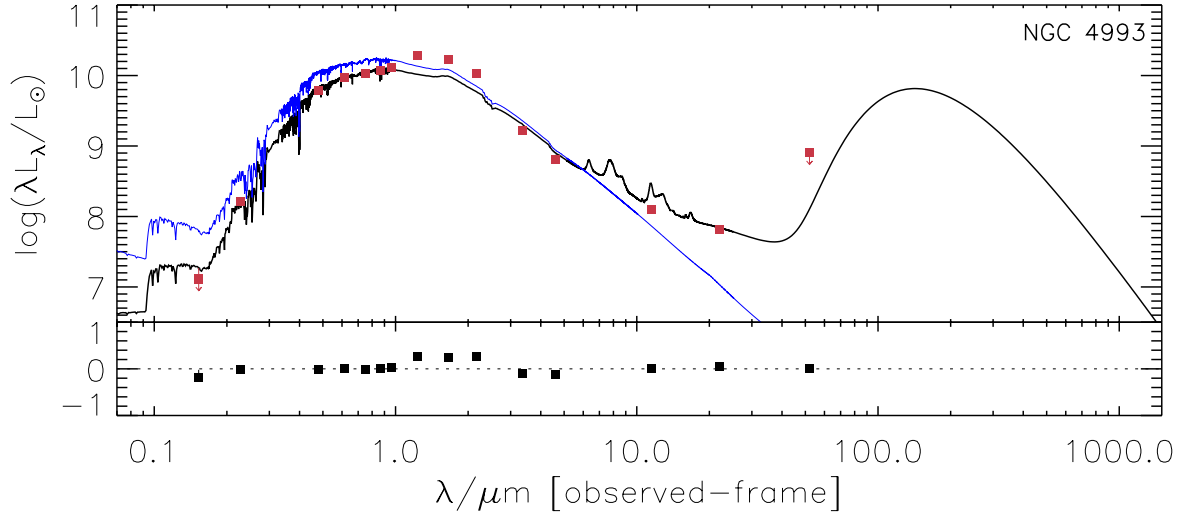


Figure S7: Spectral energy distribution obtained by combining photometric data of *GALEX*, Pan-STARRS, 2MASS, *WISE*, and *IRAS* surveys (red squares). The flux density was corrected for Galactic extinction before the fitting assuming $R_V = 3.1$ and $E(B - V) = 0.1$. We used upper limits for *GALEX*/FUV and *IRAS*/60 μm bands. The upper panel shows the unattenuated stellar spectrum (blue line) and the sum of attenuated stellar spectrum and the infrared emission (black line). The lower panel shows the residuals $(L_\lambda^{\text{obs}} - L_\lambda^{\text{model}})/L_\lambda^{\text{obs}}$ (black squares), where L_λ^{obs} and L_λ^{model} represent observed and predicted broad-band luminosity densities respectively.

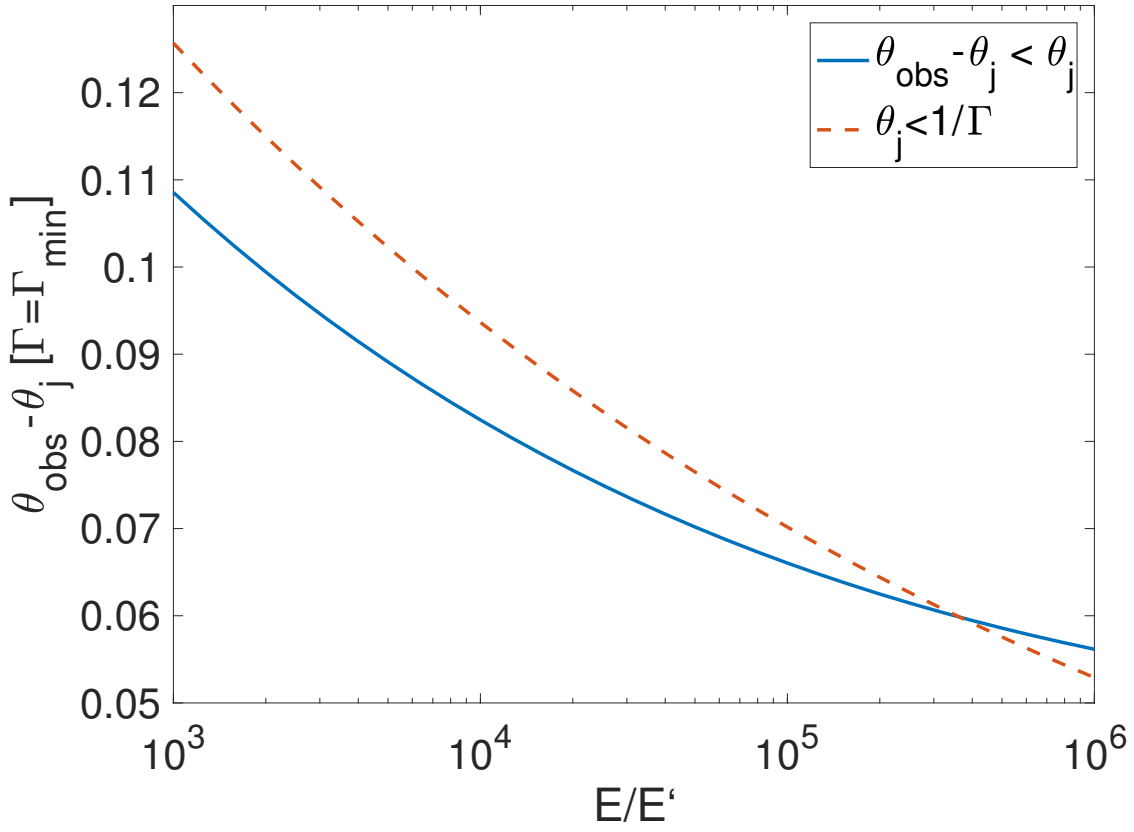


Figure S8: The maximal value of $\theta_{\text{obs}} - \theta_j$ as a function of the amplification parameter $\mathcal{A} \equiv E/E'$ for observers far and close to the jet axes (cases (i) and (iii) in equation S2). The observed values of EM170817 that we used are photon energy $E'_p = 185$ keV and γ -ray spectral index $\alpha = -0.6$ (3, 4).

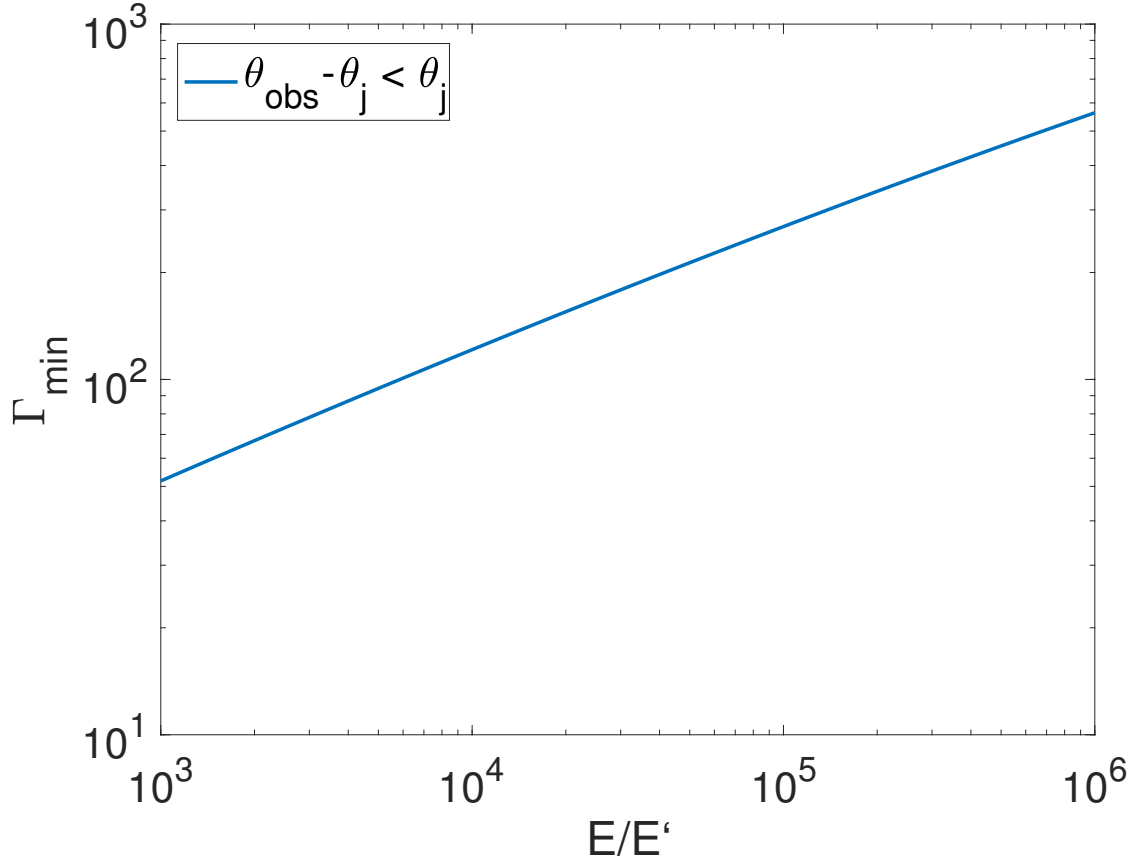


Figure S9: The minimal Lorentz factor of the jet, Γ_{\min} , required for the jet to be optically thin as a function of the amplification parameter $\mathcal{A} \equiv E/E'$ for far off-axis observers, $\theta_{\text{obs}} - \theta_j \ll \theta_j$ (case (i) in equation S2). The parameters assumed here were the same as those assumed in figure S8: photon energy $E'_p = 185$ keV and γ -ray spectral index $\alpha = -0.6$ (3, 4).

Table S3: Census of the Local Universe (CLU) galaxies within the localization volume of GW170817 (91). For each galaxy we give the coordinates (J2000), distance, far-ultraviolet (FUV) magnitude from *GALEX*, mid-infrared magnitudes from *WISE*, estimated star-formation rate (SFR) based on the FUV magnitude, estimated stellar mass based on the mid-infrared magnitudes, and probability within the GW170817 localization volume.

Galaxy	RA (deg)	DEC (deg)	D (Mpc)	FUV (AB)	WISE1 (Vega)	WISE4 (Vega)	$\log_{10}(\text{SFR})$ (FUV) ($M_{\odot}\text{yr}^{-1}$)	$\log_{10}(M_{\star})$ (M_{\odot})	Prob.
NGC 4970	196.8906	-24.0086	46.50	...	9.78	8.01	...	10.42	0.68
NGC 4830	194.3663	-19.6913	47.90	18.88	9.87	8.34	-1.32	10.41	0.75
NGC 4993	197.4487	-23.3839	41.66	20.13	9.94	7.47	-1.35	10.26	0.41
NGC 4968	196.7749	-23.6770	42.24	18.93	9.99	2.41	0.63	10.25	0.51
IC 4197	197.0180	-23.7969	43.24	...	10.07	7.45	...	10.24	0.48
IC 4180	196.7354	-23.9171	42.46	18.05	10.19	5.62	-0.58	10.17	0.60
ESO 508- G 033	199.0969	-26.5614	45.59	17.02	10.90	3.70	0.21	9.95	0.83
MCG -02-33-036	193.1066	-15.5172	53.87	19.81	11.50	7.47	-1.11	9.86	0.88
ESO 508- G 010	196.9080	-23.5790	43.04	...	11.88	5.97	...	9.51	0.44
MCG -03-33-023	194.2521	-17.3202	56.79	...	12.93	6.37	...	9.33	0.90
ESO 575- G 053	196.2705	-22.3839	36.37	16.46	11.98	6.47	-0.68	9.33	0.23
2MASX J12525109-1529300	193.2130	-15.4916	52.26	...	12.80	8.55	...	9.31	0.84
2MASX J12505229-1454238	192.7180	-14.9066	52.96	17.92	12.89	7.10	-0.79	9.29	0.89
2MASX J12573271-1942006	194.3863	-19.7002	52.39	20.65	12.96	9.18	-1.73	9.25	0.87
ESO 576- G 003	197.6488	-21.7482	42.04	...	12.65	6.59	...	9.18	0.89
UGCA 331	197.6914	-23.8657	40.82	...	12.61	7.33	...	9.17	0.47
IC 3825	192.6544	-14.4828	51.04	18.24	13.10	7.33	-0.93	9.17	0.87
ESO 575- G 055	196.6663	-22.4561	44.49	17.11	13.04	7.29	-0.79	9.07	0.32
ESO 508- G 003	196.6000	-24.1641	40.52	16.93	12.86	6.89	-0.77	9.06	0.73
ESO 508- G 019	197.4663	-24.2391	41.79	...	13.13	6.66	...	8.98	0.47
ESO 575- G 029	193.9986	-19.2691	45.21	...	13.36	7.96	...	8.96	0.78
2MASX J13073768-2356181	196.9071	-23.9384	49.73	...	13.66	8.44	...	8.92	0.75
2MFGC 10461	197.1774	-23.7756	41.39	...	13.32	8.61	...	8.90	0.40
2MFGC 10484	197.4617	-24.2419	42.31	...	13.46	...	...	8.86	0.48
2MASX J13061939-2258491	196.5805	-22.9804	41.51	17.52	13.51	7.30	-0.96	8.83	0.35
UGCA 327	196.9370	-22.8579	37.29	...	13.33	7.02	...	8.81	0.24
GALEXASC J125520.46-170546.9	193.8364	-17.0966	56.69	18.39	14.58	8.31	-1.06	8.67	0.89
WINGS J125412.84-153523.6	193.5534	-15.5899	50.96	...	14.43	8.33	...	8.64	0.82
ESO 508- G 004	196.7177	-22.8405	41.37	16.59	14.05	8.54	-0.78	8.61	0.26
ESO 508- G 014	197.1342	-23.3469	46.61	18.44	14.32	8.83	-1.31	8.60	0.50

Table S3: Census of the Local Universe (CLU) galaxies within the localization volume of GW170817 (9I), continued.

Galaxy	RA (deg)	DEC (deg)	D (Mpc)	FUV (AB)	WISE1 (Vega)	WISE4 (Vega)	$\log_{10}(\text{SFR})$ (FUV) ($M_{\odot}\text{yr}^{-1}$)	$\log_{10}(M_{\star})$ (M_{\odot})	Prob.
6dF J1254495–160308	193.7063	–16.0523	48.02	...	14.60	8.60	...	8.52	0.64
GALEXASC J125811.97–210246.3	194.5501	–21.0461	43.89	17.69	14.51	8.86	–1.13	8.47	0.90
GALEXASC J130525.30–233008.8	196.3546	–23.5025	45.90	17.44	14.73	7.16	–0.83	8.43	0.76
GALEXASC J125259.36–152150.9	193.2474	–15.3639	49.87	18.44	14.96	8.63	–1.23	8.41	0.78
GALEXASC J125301.39–151007.7	193.2552	–15.1693	53.40	20.94	15.25	8.93	–1.67	8.35	0.90
PGC45429	196.7822	–24.1104	41.50	...	14.82	9.12	...	8.30	0.65
6dF J1305235–233121	196.3478	–23.5224	41.71	17.31	14.90	8.41	–1.02	8.28	0.68
UGCA 325	196.7796	–24.1119	42.70	...	15.05	...	...	8.24	0.67
GALEXASC J130415.26–225251.3	196.0633	–22.8814	41.23	18.41	15.05	8.72	–1.40	8.20	0.57
6dF J1309177–242256	197.3241	–24.3821	40.36	...	15.23	7.34	...	8.12	0.49
UGCA 328	197.3298	–24.3866	41.03	...	15.27	8.31	...	8.11	0.50
GALEXASC J125157.02–160617.8	192.9872	–16.1047	50.30	21.04	15.85	8.20	–1.49	8.06	0.76
ESO 508– G 035	199.4497	–26.9025	37.77	17.95	15.33	9.19	–1.37	8.02	0.85
PGC45611	197.3286	–24.3846	39.81	15.87	15.55	8.29	–0.54	7.98	0.49
ABELL 1664.11:[PSE2006] 2506	196.8922	–23.8153	42.80	21.49	15.83	9.09	–1.96	7.93	0.50
GALEXASC J131426.62–271242.6	198.6106	–27.2120	29.32	18.39	15.28	8.77	–1.69	7.82	0.89
ABELL 1631:[CZ2003]B0295[024]	192.8695	–15.8723	53.56	...	16.70	8.46	...	7.77	0.87
WINGS J125701.38–172325.2	194.2558	–17.3903	26.13	...	16.83	9.31	...	7.10	0.27
HIPASS J1255–15	193.8983	–15.0175	27.32	...	...	...	...	0.00	0.83

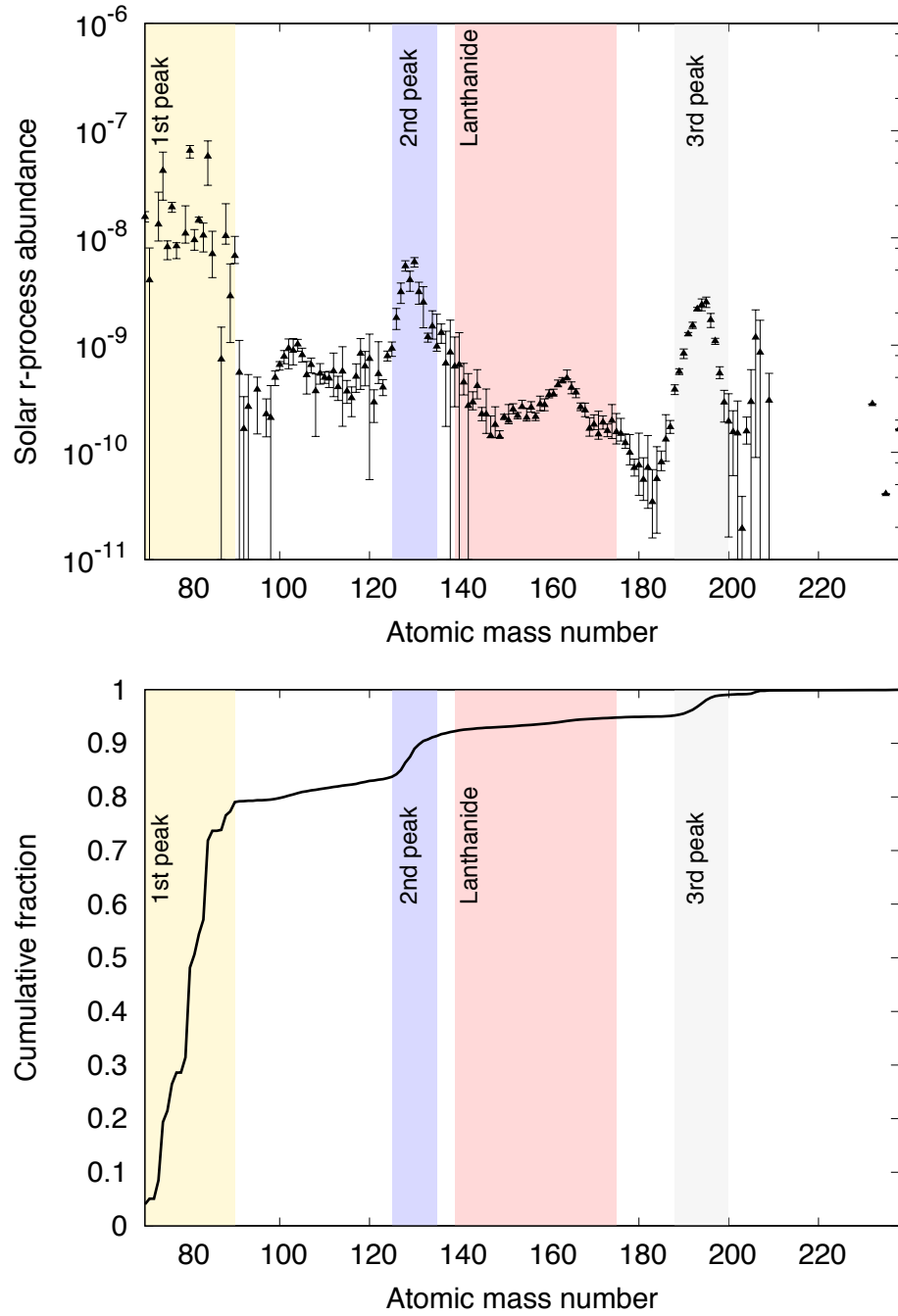


Figure S10: Top: the solar abundance pattern of r-process elements (*151*). Bottom: their cumulative distribution.

Movie S1. Animated version of Fig. 6.

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